Abstract. Current-mode (CM) and voltage-mode (VM) multiphase sinusoidal oscillator (MSO) structures using current backward transconductance amplifier (CBTA) are proposed. The proposed oscillators can generate \( n \) current or voltage signals (\( n \) being even or odd) equally spaced in phase. \( n+1 \) CBTA, \( n \) grounded capacitor and a grounded resistor are used for \( n \)-th state oscillator. The oscillation frequency can be independently controlled through transconductance \( g_m \) of the CBTA which are adjustable via their bias currents. The effects caused by the non-ideality of the CBTA on the oscillation frequency and condition have been analyzed. The performance of the proposed circuits is demonstrated on third-stage and fifth-stage MSOs by using PSPICE simulations based on the 0.25 \( \mu m \) TSMC level-7 CMOS technology parameters.

Keywords
Multiphase sinusoidal oscillator, current backward transconductance amplifier (CBTA), current-mode circuits, voltage-mode circuits, active networks.

1. Introduction

Design of multiphase sinusoidal oscillators (MSOs) has received great deal of attention in the fields of communications, signal processing, and power controllers. Numerous techniques for designing a MSO have been developed in the past two decades [1]-[17]. The circuits in [1]-[3] use operational amplifiers (op-amps) as active elements while the MSO circuits in [4]-[7] employ second-generation current conveyors (CCIs). The main drawback of the circuits in [1]-[7] is use of excessive number of resistors/capacitors. Moreover, in circuit of [1]-[3] some of the passive elements are connected in floating form which is not desirable from integrated circuit implementation point of view. There are also MSO circuits based on using current differencing transconductance amplifiers (CDTAs) [8]-[12] which all of them operate in current-mode (CM) (i.e. the output signals are currents). While the circuit in [8] has the advantage of using only grounded capacitors, the circuits in [9]-[10] employ floating capacitors/resistors. In addition the circuit in [9] requires excessive number of active elements (two for each phase) which increases the total power consumption. The MSO circuits of [11]-[12] employ multi-output CDTAs which increases the complexity of the active elements as well as the total power consumption.

There are also MSO circuits based on current differencing buffered amplifier (CDBA) [13], and current amplifiers [14]. Moreover, CM MSO circuits using bipolar junction transistors (BJTs) have been recently introduced in [15]-[17]. However due to the use of BJT technology the oscillation frequency is strictly temperature-dependent.

The most important features in the design of a MSO circuit can be summarized as follows:

(a) Number of active component per phase,
(b) Number of \( R+C \) per phase,
(c) Use of only grounded \( C \),
(d) Use of only grounded \( R \),
(e) Realizing odd and even number of phase,
(f) Electronic tunability,
(g) Free of matching between passive components,
(h) Low-output impedance for VM,
(i) High-output impedance for CM.

In this paper we present novel voltage-mode (VM) and current-mode (CM) MSOs with an arbitrary \( n \) number of the signals equally spaced in phase. They are constructed by cascading lossy integrators and an inverting amplifier implemented with a recently introduced active element namely current backward transconductance amplifier (CBTA). Therefore, \( n+1 \) CBTA, \( n \) grounded capacitors and one grounded resistor are used for realizing \( n \)-state oscillators. A comprehensive comparison of the proposed MSO circuit and previously reported ones based on the above mentioned features is given in Tab. 1.
Iz defined as voltage sources. The CBTA terminal equations can be circuit in Fig. 1(b), which involves dependent current and put terminals. This active element is equivalent to the circuit symbol of the CBTA is shown in Fig. 1, where \[\text{[18]}-\text{[27]}\]. The circuit symbol of the CBTA is shown in this active element have been reported in the literature 2010 to provide new possibilities in the circuit synthesis.

\[\varepsilon = \omega \alpha \mu \varepsilon \mu \varepsilon \]

\(\text{[26]}\). The error, \(\varepsilon\), denoted the transconductance error and \(\varepsilon\) of the transconductance section is set to 4. Therefore, the output current \(I_{o}\) can be found as:

\[I_{o} = g_{m} v_{in} = 4 \times \frac{I_{B} e_{Cox} W_{21,22} L_{21,22}}{V_{21,22}} \]

where \(\mu\) is the mobility of the carrier, \(C_{ox}\) is the gate-oxide capacitance per unit area, \(W_{21,22}\) is the effective channel width, \(L_{21,22}\) is the effective channel length of the transistors M21-M22.

\[\text{Tab. 1. Comparison with previously published MSOs (*: No use of external resistor, NA: Not applicable).}

<table>
<thead>
<tr>
<th>Ref.</th>
<th>(a)</th>
<th>(b)</th>
<th>(c)</th>
<th>(d)</th>
<th>(e)</th>
<th>(f)</th>
<th>(g)</th>
<th>(h)</th>
<th>(i)</th>
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<tbody>
<tr>
<td>[1]</td>
<td>1</td>
<td>3+1</td>
<td>Yes</td>
<td>No</td>
<td>No</td>
<td>No</td>
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<td>[2]</td>
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<td>No</td>
<td>No</td>
<td>No</td>
<td>No</td>
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<td>[3]</td>
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<td>Yes</td>
<td>No</td>
<td>No</td>
<td>NA</td>
<td></td>
</tr>
<tr>
<td>[5]</td>
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<td>2+1</td>
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<td>No</td>
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<td></td>
</tr>
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<td>[6]</td>
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<td>1+2</td>
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<td>No</td>
<td>No</td>
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<td></td>
</tr>
<tr>
<td>[7]</td>
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<td>2+1</td>
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<td>No</td>
<td>No</td>
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<td>[8]</td>
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<td>0+1</td>
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<td>*</td>
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<td>[10]</td>
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<td>Yes</td>
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<td>[11]</td>
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<td>0+1</td>
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<td>[12]</td>
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<td>[14]</td>
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<td>0+1</td>
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<td>[15]</td>
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<tr>
<td>[16]</td>
<td>1</td>
<td>0+1</td>
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<td>*</td>
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</tr>
</tbody>
</table>

\[\text{Proposed VM MSO} \quad 1 \quad 0+1 \quad \text{Yes} \quad * \quad \text{Yes} \quad \text{Yes} \quad \text{Yes} \quad \text{Yes} \quad \text{NA} \quad \text{Yes} \quad \text{Yes} \]

\[\text{Proposed CM MSO} \quad 1 \quad 0+1 \quad \text{Yes} \quad \text{Yes} \quad \text{Yes} \quad \text{Yes} \quad \text{Yes} \quad \text{Yes} \quad \text{NA} \quad \text{Yes} \quad \text{Yes} \]

2. Current Backward Transconductance Amplifier

CBTA as a new active component was introduced in 2010 to provide new possibilities in the circuit synthesis. Several analog signal processing applications using this active element have been reported in the literature. In addition, the CBTA implementation are given in Tab. 2. As seen from Fig. 2, the transistors M21-M34 are used for realizing the transconductance section, and the transistors M35-M42 are used for realizing the z-copy current section, while transistors M1-M14 form a current conveyer. In addition transistors M15-M19 are employed for biasing purpose. \(v_{in}\) is the differential input voltage \(v_{in} = v_{p} - v_{n}\), \(I_{o}\) is the output current of the transconductance section and \(I_{B}\) is the bias current. The gain of the current mirrors in the output stage of the transconductance section is set to 4. Therefore, the output current \(I_{o}\) can be found as:

\[I_{o} = g_{m} v_{in} = 4 \times \frac{I_{B} e_{Cox} W_{21,22} L_{21,22}}{V_{21,22}} \]

where \(\mu\) is the mobility of the carrier, \(C_{ox}\) is the gate-oxide capacitance per unit area, \(W_{21,22}\) is the effective channel width, \(L_{21,22}\) is the effective channel length of the transistors M21-M22.

\[\text{Tab. 2. Dimension of the CMOS transistors.}

<table>
<thead>
<tr>
<th>PMOS Transistors</th>
<th>(W(\mu m)/L(\mu m))</th>
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<tbody>
<tr>
<td>M1, M2</td>
<td>20/1</td>
</tr>
<tr>
<td>M35, M36, M37, M38</td>
<td>1.0/25</td>
</tr>
<tr>
<td>M39, M40, M41, M42</td>
<td>100/25</td>
</tr>
<tr>
<td>NMOS Transistors</td>
<td>(W(\mu m)/L(\mu m))</td>
</tr>
<tr>
<td>M5, M6, M21, M22</td>
<td>10/1</td>
</tr>
<tr>
<td>M23, M24</td>
<td>2.5/1</td>
</tr>
<tr>
<td>M25, M26</td>
<td>0.5/0.25</td>
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<tr>
<td>M27, M28</td>
<td>2.5/0.25</td>
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<tr>
<td>M29, M30</td>
<td>2/0.25</td>
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<tr>
<td>M31, M32</td>
<td>2.5/0.25</td>
</tr>
<tr>
<td>M33, M34, M35, M36, M37, M38, M39, M40, M41, M42</td>
<td>100/25</td>
</tr>
</tbody>
</table>
3. CBTA-Based MSOs

The generalized structure of an \( n \)-phase sinusoidal oscillator is shown in Fig. 3 [1], [2], [4], [7]. It consists of \( n \) cascaded lossy integrators and a unity gain inverting amplifier in a closed loop. For lossy integrator sections \( k \) is the low-frequency stage gain, and \( T \) is the system time constant [1]. The system loop gain is given by:

\[
L(s) = \frac{V_{o0}(s)}{V_{io}(s)} = \left( \frac{k}{1 + Ts} \right)^n \cdot (3)
\]

For oscillation to sustain, the Barkhausen criteria must be satisfied [28]:

\[
- \left( \frac{k}{1 + Ts} \right)^n = 1 \cdot (4)
\]

That is

\[
(1 + j \omega_o T)^n + k^n = 0 \cdot (5)
\]

Equation (5) can be rewritten as:

\[
(1 + \omega_o^2 T^2)^{n/2} \cdot e^{j \pi \tan^{-1} \omega_o T} = k^n \cdot e^{j \pi} \cdot (6)
\]

Thus the oscillation condition (OC) and oscillation frequency (OF) are found as:

**OC:** \( k = (1 + \omega_o^2 T^2)^{1/n} \cdot (7a) \)

**OF:** \( \omega_o = \frac{T}{1 + \tan^{-1} \left( \frac{T}{n} \right)} \cdot (7b) \)

Substituting \( \omega_o \) of (7b) in (7a) gives:

\[
OC: k = \left[ 1 + \tan^{2} \left( \frac{T}{n} \right) \right]^{1/n} \cdot (8)
\]

From (8) it can be seen that the oscillation condition depends on the number of the oscillation phases, \( n \). It is obvious that the oscillation occurs when \( n \geq 3 \). The output number of the oscillator is \( n \), each output voltage \( V_{o0} \) is shifted in phase by \( 180^\circ/n \).

The CBTA realization of the MSO constitutes of two sub-circuits, i.e. lossy integrator and inverting amplifier shown in Fig. 4. The voltage gains of the circuits in Figs. 4(a) and 4(b) can be found respectively as:

\[
\frac{V_{o_i}}{V_{o_{i-1}}} = \frac{\mu_w g_{mi}/C_i}{1 + s(C_i + \mu_w g_{mi})} = \frac{1}{1 + s C_i/\mu_w g_{mi}} \cdot (9a)
\]

and

\[
\frac{V_o}{V_i} = -\mu_w g_{mf} R_f = -K \cdot (9b)
\]

where \( g_{mf} \) is the transconductance of the CBTA used in the inverting amplifier of Fig. 4(b). Moreover, from (9b) \( K = \mu_w g_{mf} R_f \) is the gain (in magnitude) of the VM inverting amplifier shown in Fig. 4(b).
For oscillation to sustain, the Barkhausen criteria must be satisfied, that is:

\[-K \left[ \frac{1}{1 + s \frac{C_i}{μwS_{mi}}} \right] = 1. \quad (11)\]

Therefore, the oscillation condition and the oscillation frequency are found from (11) as:

OC: \( K = \left[ 1 + \frac{α_n^2 C_i^2}{μwS_{mi}^2} \right]^{n/2}, \) \quad (12a)

OF: \( ω_o = \frac{C_i}{μw} \tan \left( \frac{π}{n} \right). \) \quad (12b)

Substituting \( ω_o \) of (12b) into (12a) gives:

OC: \( K = \left[ 1 + \tan^2 \left( \frac{π}{n} \right) \right]^{n/2} \) \quad (13)

Further, from (12b) and (13) it can be seen that the oscillation frequency can be independently controlled through equal valued \( g_{mi} \) parameters which are electronically adjustable by changing the bias currents of the CBTA.

The output impedance of the proposed structure can be found as:

\( Z_{o_1} = Z_{n_i} / Z_{p_1,i} / Z_{w_i}. \) \quad (14)

In ideal case \( Z_{w_i} = 0 \), thus \( Z_{o_1} = 0 \).

The second proposed CBTA-based MSO circuit which operates in current-mode can be obtained using two sub-circuits shown in Fig. 6.

The current gains of the circuits in Figs. 6(a) and 6(b) can be found respectively as follows:

\[ \frac{I_o}{I_{o_1}} = \frac{α_n g_{mi} / C_i}{s + g_{mi} / C_i} = \frac{α_n}{1 + s C_i / g_{mi}} \] \quad (15a)

and

\[ \frac{I_o}{I_i} = -g_{mf} R_f = -K \] \quad (15b)

where \( g_{mf} \) is the transconductance of the CBTA used in the inverting amplifier of Fig. 6(b). From (15b) \( K = g_{mf} R_f \) which is the gain of the CM inverting amplifier shown in Fig. 6(b).
above CBTA-based sub-circuits in accordance to the block diagram of Fig. 3. The resulting circuits are shown in Fig. 7. The closed loop gains of the circuits in Fig. 7 can be expressed as:

\[
L(s) = -g_m R_f \left\{ \frac{\alpha_n}{1 + sC_i / g_m} \right\}^n = -K \left\{ \frac{\alpha_n}{1 + sC_i / g_m} \right\}^n
\]

(16)

For oscillation to sustain, the Barkhausen criteria must be satisfied, that is:

\[
-K \left\{ \frac{\alpha_n}{1 + sC_i / g_m} \right\}^n = 1
\]

(17)

Therefore, the oscillation condition and the oscillation frequency are found from (17) as:

**OC:**

\[
K = \alpha_n^{-n} \left( 1 + \frac{2\alpha_n^2 C_i^2}{g_m} \right)^{\frac{n}{2}}
\]

(18a)

**OF:**

\[
\omega_o = \frac{g_m}{C_i} \tan \left( \frac{\pi}{n} \right).
\]

(18b)

Substituting \(\omega_o\) of (18b) into (18a) gives **OC:**

\[
K = \alpha_n^{-n} \left( 1 + \tan^2 \left( \frac{\pi}{n} \right) \right)^{\frac{n}{2}}
\]

(19)

Again from (18b) and (19) it can be realized that the oscillation frequency can be independently controlled through equal valued \(g_m\) parameters which are electronically adjustable by changing the bias currents of the CBTAs.

The output impedance of the proposed structure can be found as:

\[
Z_{oi} = R_z / (1/sC_z), \quad i = 1, 2, \ldots, n
\]

(20)

where \(R_z\) and \(C_z\) are the z-terminal resistances and capacitance of the CBTAs. In ideal case \(Z_{oi} = \infty\).

### 4. Simulation Results

To verify the proposed MSOs, the CBTAs are simulated using the CMOS-based CBTA circuit shown in Fig. 2 with DC power supply voltages equal to \(V_{DD} = -V_{SS} = 1.5\) V. The simulations are performed by using the PSPICE based on 0.25 \(\mu\)m level-7 TSMC CMOS technology parameters. Some of the technology parameters used in PSPICE simulations are given as follows: threshold voltage \(V_{TH} = 0.3894\) V, low field mobility \(U_0 = 302.356\) cm\(^2\)/Vs, and gate oxide thickness \(T_{ox} = 5.714 \times 10^{-9}\) m for the NMOS transistor in addition to \(V_{TH} = -0.567\) V, \(U_0 = 107.1614\) cm\(^2\)/Vs, and \(T_{ox} = 5.714 \times 10^{-9}\) m for the PMOS transistor.

In this simulation, the voltage-mode MSO circuit of Fig. 5(b) for \(n = 3\) is designed with the passive component values of \(C_1 = C_2 = C_3 = 50\) pF and \(R_f = 16\) k\(\Omega\), all bias currents of the CBTAs are chosen as 50 \(\mu\)A (\(g_m = 0.5\) mS).

Fig. 8 shows the voltage outputs of each stage in the MSO. In this case \((n = 3)\) with all the above parameters, the oscillation frequency is obtained as 2.56 MHz from the simulation which is close to the theoretical value of 2.756 MHz. The phase differences among the outputs for \(n = 3\) is in the vicinity of 120 degree. It should be mentioned that no amplitude limiter circuit is used so the output voltage at \(v_{o1}\) is a little distorted. The THD values for \(v_{o1}, v_{o2}, v_{o3}\) voltage outputs are 2.1%, 1.7% and 0.75%, respectively.

The simulation results for \(n = 5\) with same component values (except \(R_f\) which is 5.8 k\(\Omega\)) is also given in Fig. 9. The oscillation frequency is obtained as 1.13 MHz from the simulation which is close to the theoretical value of 1.156 MHz.

The FFT spectrum of the each output signals for \(n = 3\) are shown in Figs. 10-12. As seen from Figs. 8-12, the oscillations are observed to be quite stable and the simulation results confirm the workability of the proposed oscillator circuit.

![Fig. 8. Output voltages of the proposed VM MSO for \(n = 3\).](image-url)
For the current-mode MSO circuit, the simulations are repeated. The MSO circuit for \( n = 3 \) is designed with the passive component values \( C_1 = C_2 = C_3 = 10 \text{ pF} \) and \( R_f = 16 \text{ k}\Omega \), all bias currents of the CBTAs are chosen as \( 50 \mu\text{A} \left( g_{m} = 0.5 \text{ mS} \right) \).

Fig. 13 shows the current outputs of each stage in the MSO. In this case \((n = 3)\) with all the above parameters, the oscillation frequency is obtained as 10.8 MHz from the simulation while the theoretical value is 13.77 MHz. The difference between theoretical and simulated values can be attributed to the parasitic effects of the CBTAs. The phase differences among the outputs for \( n = 3 \) is in the vicinity of 120 degree. The THD values for \( i_{o1}, i_{o2}, i_{o3} \) voltage outputs are 5.57%, 1.93% and 0.98%, respectively. The FFT spectrum of the each current output signals for \( n = 3 \) are shown in Fig. 14. As seen from Figs. 13 and 14, the oscillations are observed to be quite stable and the simulation results confirm the workability of the proposed current-mode oscillator circuit.

Due to the non-idealities of the CBTAs, some discrepancies exhibit between theoretical and simulation results as shown in Figs. 8-14. In order to find operating point and non-idealities of CBTAs, the PSPICE simulations are also done by using above mentioned transistor model. As a result, corner frequencies are \( \omega_{\alpha p} = 5300, \omega_{\alpha n} = 6000, \omega_{gm} = 5000 \) and \( \omega_{\mu} = 3015 \text{ Mrad/s} \) and errors of these gains are \( \varepsilon_{\alpha p} = -0.0142, \varepsilon_{\alpha n} = 0.003, \varepsilon_{gm} = 0.0184 \) and \( \varepsilon_{\mu} = -0.0035 \). For low-frequency application \( \alpha_{\alpha}, \alpha_{gm}, \mu_{\alpha} \) and \( \mu_{\alpha} \) can be assumed to be the constants with values \( 1 - \varepsilon_{\alpha p} = 1.0142, 1 - \varepsilon_{\alpha n} = 0.997, 1 - \varepsilon_{gm} = 1.9816 \) and \( 1 - \varepsilon_{\mu} = 1.0035 \), respectively.
Therefore, the maximum operating frequency of the CBTA can be found as follows $f_{\text{max}} = \min\{f_{\alpha p}, f_{\alpha n}, f_{\mu}\} \approx 480$ MHz. The frequency responses of the transconductance gain $\mu = I_z / (V_p - V_n)$, the voltage gain $\mu_w = V_w / V_z$, and the current gains $\alpha_p = I_p / I_w$, $\alpha_n = I_n / I_w$ are given in Figs. 15 (a-d), respectively.

The DC transconductance transfer characteristic of $i_z$ against $v_{p-n}$ when $g_m = 0.5$ mS, and DC voltage transfer characteristic of $v_w$ against $v_z$ are shown in Fig. 16a. For this simulation, a DC voltage sweep between $-1$ V $\leq (v_p - v_n) \leq 1$ V was applied to the $p$ and $n$ terminals of the CBTA. The output $z$ terminal current is measured while 1 T$\Omega$ resistor is connected to the $w$ output of the CBTA and the output $z$ terminal is grounded. As a result, the CBTA works linearly between $-200$ $\mu$A $\leq i_z \leq 200$ $\mu$A and $-0.4$ V $\leq v_p - v_n \leq 0.4$ V with an error less than 1 % for $g_m = 0.5$ mS. The DC characteristics such as plots of $v_w$ against $v_z$ for the proposed CBTA are obtained as shown in Fig. 16b. For this simulation, a DC voltage sweep between $-2$ V $\leq v_z \leq 1.5$ V is applied to the $z$ terminal of the CBTA. The output $w$ terminal voltage is measured while 1 T$\Omega$ resistor is connected to the $w$ output of the CBTA and the $p$ and $n$ terminals are grounded. As a result, the CBTA works linearly between $-1.5$ V $\leq v_w \leq 1$ V with an error less than 1 % for $g_m = 0.5$ mS.

The DC current transfer characteristics of $i_p$ and $i_n$ against $i_w$ for the proposed CBTA are obtained as shown in Figs. 16c and 16d. For these simulations, a DC current sweep between $-1$ mA $\leq i_p \leq 1.5$ mA is applied to the $w$ terminal of the CBTA. The input $p$ and $n$ terminal currents are measured while the $z$, $p$ and $n$ terminals are grounded. As a result, the CBTA works linearly between $-750$ mA $\leq i_p \leq 1.3$ mA and $-750$ mA $\leq i_n \leq 1.1$ mA with an error less than 1 % for $g_m = 0.5$ mS.

The simulation results also show that the values of the transconductance gain $g_m$ of the CBTA are between 28 $\mu$S and 1.2 $\mu$S.

The CBTA has parasitic resistances and capacitances as shown in Fig. 17. The parasitic resistances and capacitances values of the CBTA are given in Tab. 3.
5. Conclusion

Novel current and voltage-mode versatile generalized \( n \)-phase sinusoidal oscillator structures using CBTA\s are proposed. The proposed circuits use grounded resistors and capacitors which are suitable for IC implementations. They generate \( n \) current or voltage signals which are equally spaced in phase, \( n \) can be chosen as even or odd number. The oscillation frequency can be electronically controlled using bias currents of CBTA\s.

The above properties make the proposed MSOs attractive for circuit designers and engineers.

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References


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