*KMUTNB Int J Appl Sci Technol, Vol. 11, No. 3, pp. 209–216, 2018*

Research Article

# Single CDCTA Based Electronically Adjustable Current-mode Quadrature Sinusoidal Oscillator

David Siriphot*, Nattapon Pookrongtong and Wisit Lumchanao
Department of Technology Electronics, Faculty of Industrial Technology, Buriram Rajabhat University, Buriram, Thailand

* Corresponding author. E-mail: dave_david@hotmail.co.th

DOI: 10.14416/j.ijast.2018.06.003
Received: 29 January 2018; Accepted: 3 May 2018; Published online: 14 June 2018

## Abstract

The realization of the current-mode quadrature sinusoidal oscillator was presented in this paper. In this design, a single active building block, named Current Differencing Cascaded Transconductance Amplifier (CDCTA) was used with grounded resistor and two grounded capacitors. The proposed circuit was a simple structure which was attractive for integrated circuit implementation. The proposed oscillator could generate two sinusoidal signals with 90°degree phase difference. The output current nodes were high impedance which was ideal for cascading in the current-mode circuit without the requirement of the current buffers. Moreover, the control of the Frequency of Oscillation (FO) and the Condition of Oscillation (CO) were orthogonally and electronically via the DC bias current of CDCTA. The workability of the proposed sinusoidal oscillator was verified with PSpice in which simulation results agree well with theoretical expectations.

**Keywords**: Sinusoidal oscillator, Electronic adjustability, CDCTA

## 1 Introduction

The sinusoidal signals play an important role in communication, sound system, instrumentation, control system, etc. [1]. The circuit which generates the sinusoidal wave is known as the oscillator. The quadrature oscillator which provides two sinusoidal signals with 90° degree phase difference is known as the quadrature oscillator. This oscillator is important for telecommunication systems such as Quadrature Amplitude Modulation (QAM) system, Single-SideBand (SSB) generators, etc. [2].

The current-mode active building blocks have been widely used to design the high performance analog signal processing circuit [3]–[6]. This is because the current-mode circuits provide many advantages when they are compared to the voltage-mode ones such as low voltage operation, good performance frequently, large dynamic range, simple circuitry, etc. [7], [8]. Many principles of the current-mode Active Building Block (ABB) have been proposed in [9]. Recently, the new active building block, namely Current Differencing Cascaded Transconductance Amplifier (CDCTA) is introduced [10]. This current-mode device is the modification of the well-known active building block, Current Differencing Transconductance Amplifier (CDTA) presented by Biolek [3]. The CDCTA is the real current-mode device of which its input and outputs are current. The first and second transconductance ($g_m$) of CDCTA provide the flex*ib*ility for a designer to realize the current-mode circuit with a minimum active element. The current-mode signal processing circuits using CDCTA have been found in the literature. The current-mode nth-order filter is proposed in [10], [11]. The CDCTA based multiphase sinusoidal oscillators are introduced in [12]–[15].

Please cite this article as: D. Siriphot, N. Pookrongtong, and W. Lumchanao, "Single CDCTA based electronically adjustable current-mode quadrature sinusoidal oscillator," *KMUTNB Int J Appl Sci Technol*, vol. 11, no. 3, pp. 209–216, Jul.–Sep. 2018.

**Table 1**: Comparison of quadrature sinusoidal oscillator using the family of CDTA

| Reference | No of ABB | No of R+C | Independent/Orthogonal Tune of CO and FO | Grounded C Only | No Need of Plus and Minus Terminal ABB |
|---|---|---|---|---|---|
| [16] | 2 | 4+2 | ✓ | × | × |
| [17] | 2 | 0+2 | ✓ | ✓ | × |
| [18] | 3 | 0+2 | ✓ | ✓ | × |
| [19] | 1 | 1+2 | × | × | × |
| [20] | 2 | 1+2 | ✓ | ✓ | × |
| [21] | 2 | 0+2 | × | ✓ | × |
| [22] | 1 | 1+2 | × | × | ✓ |
| [23] | 2 | 0+2 | × | ✓ | ✓ |
| [24] | 2 | 1+2 | ✓ | ✓ | × |
| [25] | 3 | 0+2 | ✓ | ✓ | × |
| [26] | 2 | 0+2 | × | × | ✓ |
| [27] | 2 | 0+2 | × | × | × |
| [28] | 1 | 0+2 | × | ✓ | × |
| [29] | 3 | 0+2 | ✓ | ✓ | × |
| [30] | 3 | 0+3 | ✓ | ✓ | × |
| [31] | 3 | 0+2 | × | ✓ | × |
| [32] | 1 | 0+3 | ✓ | ✓ | ✓ |
| [33] | 1 | 0+2 | × | ✓ | ✓ |
| This work | 1 | 1+2 | ✓ | ✓ | ✓ |

The current-mode quadrature sinusoidal oscillators using the family of CDTA have been found in the literature [16]–[32]. In [16], the current-mode quadrature oscillator based on two first-order all pass filters is presented. The resistorless-oscillators are presented in [17], [18], [21], [23] and [25]–[33]. The single active element-based quadrature oscillators are proposed in [19], [22], [28], [32] and [33]. The current-mode oscillator in [20] and [24] consists of two CDTAs, one resistor and two grounded resistor. The review of these topologies is shown in Table 1.

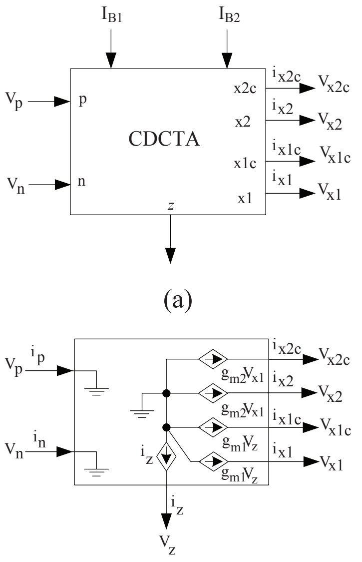
The main intention of this paper was to propose the current-mode sinusoidal oscillator which employs a single CDCTA, one grounded resistor and two grounded capacitors. Using only grounded passive element was desirable in IC implementation. The control of frequency of oscillation was electronically done without affecting the condition of oscillation. The workability of the proposed current-mode quadrature oscillator was analyzed in detail using PSpice software.

## 2 Circuit Description

The CDCTA was the versatile current-mode active building block of which input and output current. The low input impedance current terminals were $p$ and $n$. The high output impedance current terminals are $z$, $x_1$ and $x_2$. The difference of input currents from $p$ and $n$ terminal would be sent to $z$ terminal. The voltage at $z$ terminal would be converted to be the current at $x_1$ terminal via the first transconductance ($g_{m1}$). The voltage at $x_2$ terminal would be converted to be the current via the second transconductance ($g_{m2}$). The $g_{m1}$ and $g_{m2}$ were respectively controlled by DC bias current $I_{B1}$ and $I_{B2}$. To extend the use of the $x_1$ and $x_2$ terminal, the current of these terminals would be copied to $x_{c1}$ and $x_{c2}$ respectively. Figure 1(a) showed the symbolic representation of CDCTA and Figure 1(b) showed its equivalent circuit. The electrical terminal relationships of CDCTA were given as follows [10]

$$\begin{bmatrix} V_p, V_n \\ I_z \\ I_{x1}, I_{x1c} \\ I_{x2}, I_{x2c} \end{bmatrix} = \begin{bmatrix} 0 & 0 & 0 & 0 \\ 1 & -1 & 0 & 0 \\ 0 & 0 & g_{m1} & 0 \\ 0 & 0 & 0 & g_{m2} \end{bmatrix} \begin{bmatrix} I_p \\ I_n \\ V_z \\ V_{x1} \end{bmatrix} \tag{1}$$

For the BJT CDCTA, the $g_{m1}$ and $g_{m2}$ were respectively controlled by the DC bias currents $I_{B1}$ and $I_{B2}$ as follows [Equation (2)]:



(a)

(b)

**Figure 1**: (a) CDCTA electrical symbol (b) its equivalent circuit.

$$g_{m1} = \frac{I_{B1}}{2V_T}; g_{m2} = \frac{I_{B2}}{2V_T} \tag{2}$$

where $V_T$ is the thermal voltage.

The design of the proposed oscillator was focused on the use of a single active building block with the grounded passive elements. Also, the active element should not contain the plus and minus terminal to reduce the number of transistors in CDCTA. With above requirement, the proposed oscillator was successfully realized as shown in Figure 2. The proposed circuit consisted of only one CDCTA, one grounded resistor and two grounded capacitors. The CDCTA used in this design contains only the plus terminal. The output currents $I_{o1}$ and $I_{o2}$ flew out from the high impedance node connected to the other current-mode circuit without the requirement of the current buffers. From Figure 2 and using Equation (1), the characteristic equation was obtained as follows:

$$s^2C_1C_2R + sC_2\left(1 - g_{m1}R\right) + Rg_{m1}g_{m2} = 0 \tag{3}$$

Considering Equation (3), the frequency of oscillation could be presented with the Equation (4).

$$f_0 = \frac{1}{2\pi}\sqrt{\frac{g_{m1}g_{m2}}{C_1C_2}} \tag{4}$$

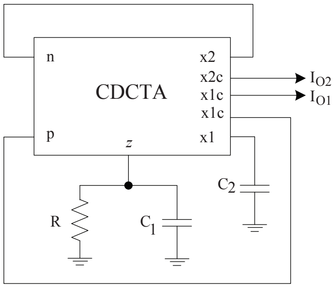


**Figure 2**: Proposed current-mode quadrature sinusoidal oscillator.

Considering Equation (3), the condition of oscillation could be presented with the Equation (5).

$$1 - g_{m1}R \le 0 \tag{5}$$

Substituting the $g_{m1}$ and $g_{m2}$ as described in Equation (2) into Equations (4) and (5), the frequency and condition of oscillation ware presented as below [Equations (6) and (7)]:

$$f_0 = \frac{1}{4\pi V_T}\sqrt{\frac{I_{B1}I_{B2}}{C_1C_2}} \tag{6}$$

and

$$1 - \frac{I_{B1}}{2V_T}R \le 0 \tag{7}$$

It was found that the frequency of oscillation could be electronically tuned by adjusting the bias current $I_{B2}$ without affecting the condition of oscillation while the resistor $R$ was used to control the condition of oscillation without affecting the frequency of oscillation. Moreover, the linear tune of the frequency of oscillation was achieved by simultaneously adjusting bias current $I_{B1}$ and $I_{B2}$ ($I_{B1} = I_{B2}$). However, the resistor $R$ was also changed to achieve the oscillation.

The ratio of output current $I_{o1}$ and $I_{o2}$ was obtained as follows:

$$\frac{I_{o2}}{I_{o1}} = \frac{g_{m1}}{sC_2} \tag{8}$$

It was evident from Equation (8) that the phase difference of $I_{o1}$ and $I_{o2}$ is 90° degree. This confirmed that the sinusoidal output current was quadrature waveform where the output current $I_{o1}$ led the output current $I_{o2}$ to 90° degree. At the frequency of oscillation ($\omega_0$), the magnitude of the ration of output current was obtained as below:

$$\left|\frac{I_{o2}}{I_{o1}}\right| = \sqrt{\frac{g_{m1}C_1}{g_{m2}C_2}} \tag{9}$$

It should be noted from Equation (9) that the $g_{m1}$ and $g_{m2}$ should be simultaneously tuned to keep the constant magnitude of ration of output current.

## 3 Non-ideal Analysis

To study the influence of non-ideal properties of CDCTA to the performance of the proposed oscillator, the tracking error of CDCTA was taken into account. For the non-ideal case, the CDCTA's properties were written as below:

$$\begin{bmatrix} V_p, V_n \\ I_z \\ I_{x1}, I_{x1c} \\ I_{x2}, I_{x2c} \end{bmatrix} = \begin{bmatrix} 0 & 0 & 0 & 0 \\ \alpha_p & -\alpha_n & 0 & 0 \\ 0 & 0 & \beta_1 g_{m1} & 0 \\ 0 & 0 & 0 & \beta_2 g_{m2} \end{bmatrix} \begin{bmatrix} I_p \\ I_n \\ V_z \\ V_{x1} \end{bmatrix} \tag{10}$$

where, $\alpha_p = 1 - \varepsilon_p$, $\alpha_n = 1 - \varepsilon_n$ and $\beta_i = 1 - \varepsilon_i$. Here, $\varepsilon_p$, $\varepsilon_n$ and $\varepsilon_i$ are current and voltage tracking error. Taking into account these parameters, the characteristic equation of the proposed oscillator was presented as below:

$$s^2 C_1 C_2 R + sC_2\left(1 - \alpha_p \beta_1 g_{m1} R\right) + \alpha_n \beta_1 \beta_2 R g_{m1} g_{m2} = 0 \tag{11}$$

Considering Equation (10), the frequency of oscillation can be given by [Equation (12)]:

$$f_0 = \frac{1}{2\pi}\sqrt{\frac{\alpha_n \beta_1 \beta_2 g_{m1} g_{m2}}{C_1 C_2}} \tag{12}$$

Considering Equation (10), the condition of oscillation could be presented with the Equation (13).

$$1 - \alpha_p \beta_1 g_{m1} R \le 0 \tag{13}$$

The ratio of output current $I_{o1}$ and $I_{o2}$ is obtained as follows:

$$\frac{I_{o2}}{I_{o1}} = \frac{\beta_1 g_{m1}}{sC_2} \tag{14}$$

The effect of the parasitic resistance and capacitance in CDCTA is also studied in this section. Taking into account these parasitic elements, the characteristic equation of the proposed oscillator was presented as below [Equation (15)]:

$$Y_1 Y_2\left(1 + Y_{x2} R_n\right) - \frac{g_{m1} Y_2\left(1 + Y_{x2} R_n\right)}{\left(1 + Y_{xc1} R_p\right)} + g_{m1} g_{m2} = 0 \tag{15}$$

where $Y_1 = s\left(C_1 + C_z\right) + G_z + G$,
$Y_2 = s\left(C_2 + C_{x1}\right) + G_{x1}$, $Y_2 = s\left(C_2 + C_{x1}\right) + G_{x1}$,
$Y_{x2} = sC_{x2} + G_{x2}$ and $Y_{xc1} = sC_{xc1} + G_{xc1}$.

From Equation (14), if the operating frequency ($f_{op}$) is much less than $\frac{R_{x2} + R_n}{2\pi C_{x2} R_{x2} R_n}$ and $\frac{R_{xc1} + R_p}{2\pi C_{xc1} R_{xc1} R_p}$, the characteristic equation of the proposed oscillator was presented as below:

$$\left\{\begin{matrix} s^2 C_1^* C_2^* + s\left[C_2^*\left(G_z + G - g_{m1}\right) + C_1^* G_{x1}\right] + \\ G_{x1}\left(G_x - G\right) - g_{m1} G_{x1} + g_{m1} g_{m2} \end{matrix}\right\} = 0 \tag{16}$$

where $C_1^* = C_1 + C_z$ and $C_2^* = C_2 + C_{x1}$. Considering Equation (16), the frequency of oscillation and the condition of oscillation was presented as below [Equations (17) and (18)]:

$$f_0 = \frac{1}{2\pi}\sqrt{\frac{G_{x1}\left(G_x - G\right) - g_{m1} G_{x1} + g_{m1} g_{m2}}{\left(C_1 + C_z\right)\left(C_2 + C_{x1}\right)}} \tag{17}$$

and

$$\left(C_2 + C_{x1}\right)\left(G_z + G - g_{m1}\right) + G_{x1}\left(C_1 + C_z\right) \le 0 \tag{18}$$

The current/voltage tracking errors and parasitic elements affect the operating frequency, frequency of oscillation and condition of oscillation. To alleviate the effect of these parameters, the internal construction of CDCTA should be carefully designed by using the high performance current mirror to achieve the high impedance output port. Also, the value of capacitors $C_1$ and $C_2$ should be greater than the value of parasitic capacitance.

## 4 Simulation Results

PSpice simulation had been carried out to verify the functionality of the proposed oscillator in Figure 2.

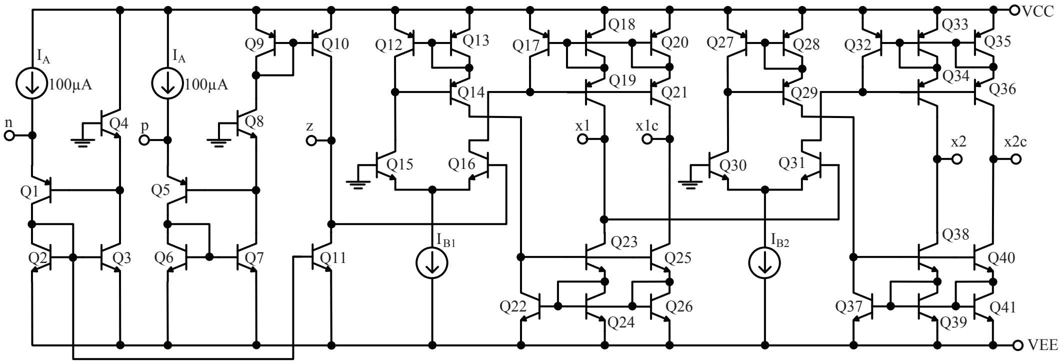


**Figure 3**: Internal construction of CDCTA.

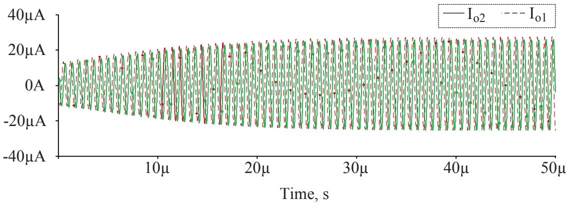


**Figure 4**: The quadrature sinusoidal output current during steady time.

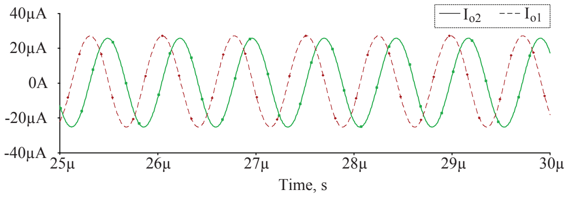


**Figure 5**: The quadrature sinusoidal output current during steady time.

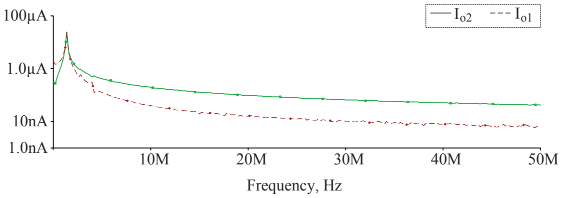


**Figure 6**: The spectrum of quadrature sinusoidal output current.

The CDCTA was realized by the BJT implementation of Figure 3. The simulations use the BJT models from AT&T CBIC-R, NR200N for NPN transistors and PR200N for PNP transistors [34]. The voltage supplies of the proposed circuit were taken as $V_{CC}$ = 2 V and $V_{EE}$ = –2 V. In the current differencing state of CDCTA, DC bias current ($I_A$) was set to 200 µA. DC bias currents, $I_{B1}$ and $I_{B2}$ to control the $g_{m1}$ and $g_{m2}$ were set to 108 µA and 100 µA, respectively. The capacitances ($C_1$ and $C_2$) and resistance ($R$) were chosen as 0.2 nF and 0.5 kΩ, respectively. With these chosen parameters, the simulation result of the quadrature sinusoidal output current during the initial time was shown in Figure 4 and the output current during steady state was shown in Figure 5. Also, its output spectrum was illustrated in Figure 6. The simulated frequency of oscillation was 1.36 MHz. The theoretical value of the frequency of oscillation in Equation (6) was 1.56 MHz. The deviation of theoretical and simulated value was 12.85%. This stems from the non-ideal properties of the CDCTA as analysis in Equation (11). The Total Harmonic Distortions (THD) for the sinusoidal output current $I_{o1}$ and $I_{o2}$ were 0.519 and 0.959%, respectively. To minimize the THD and stabilize the amplitude of quadrature output current, the Automatic Gain Control (AGC) was required. The implement of the AGC circuit could be realized by using CDTA as proposed in [22]. The total power consumption was 6.13 mW. The adjustment of DC bias current $I_{B2}$ to tune the frequency of oscillation had been done by changing the $I_{B2}$ for three values, 50, 100 and 150 µA. Having chosen $I_{B2}$ values, the simulated frequencies of oscillation were 0.966 MHz, 1.36 MHz and 1.652 MHz, respectively. The simulation result of the sinusoidal output $I_{o1}$ and its spectrums were shown in Figures 7 and 8, respectively. With theses $I_{B2}$ values, the THDs were 0.805, 0.519 and 0.667%, respectively. Also the simulation result of the sinusoidal output $I_{o2}$ and its spectrums were shown in Figures 9 and 10,

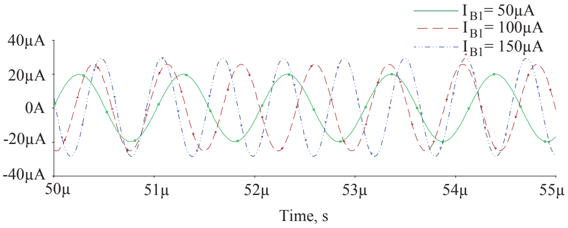


**Figure 7**: The sinusoidal output current $I_{o1}$ with different values of $I_{B2}$.

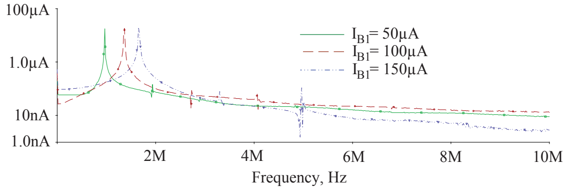


**Figure 8**: The spectrum of sinusoidal output current $I_{o1}$ in Figure 7.

respectively. With theses $I_{B2}$ values, the THDs were 1.727, 0.959 and 0.6638%, respectively. It was found from the results in Figures 7–10 that the frequency of oscillation could be controlled by the $I_{B2}$ as analyzed in Equation (6). The output resistance (at low frequency) of node $Io_1$ and $I_{o2}$ are 718.175 kΩ and 780.763 kΩ, respectively.

## 5 Conclusion

A current controlled current-mode quadrature sinusoidal oscillator was presented. The proposed circuit consisted of a single current differencing cascaded transconductance amplifier, a grounded resistor and two grounded capacitors. The workability of the proposed circuit was investigated by PSpice simulation. From the PSpice simulation results, it could be concluded that the proposed current-mode quadrature oscillator provided some advantages over the existing CDCTA based sinusoidal oscillator. First, the frequency of oscillation and the condition of oscillation were electronically controlled. Secondly, the proposed oscillator comprised only a single active element and grounded passive elements thus makes it very suitable for IC fabrication. Thirdly, the proposed circuit did not require plus and minus terminal of active device. Fourthly, the output current nodes were high impedance which was attractive for cascading without the use of buffer device.

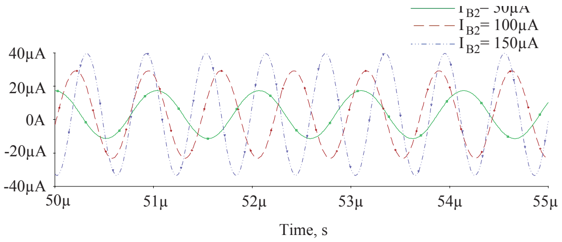


**Figure 9**: The sinusoidal output current $I_{o2}$ with different values of $I_{B2}$.

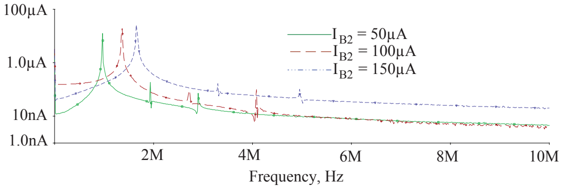


**Figure 10**: The spectrum of sinusoidal output current $I_{o1}$ in Figure 9.

## Acknowledgments

The authors would like to thank the anonymous reviewers for their valuable comments and suggestions to improve the quality of the paper. Also, the authors would like to express sincere thanks to Buriram Rajabhat University and the National Research Council of Thailand for providing the research fund. The research project with the ID 184041 had been conducted successfully because of their budget support.

## References

[1] A. S. Sedra and K. C. Smith, *Microelectronic Circuits*. New York: Oxford University Press, 1998.

[2] A. Lahiri, W. Jaikla, and M. Siripruchyanun, “First CFOA-based explicit-current-output quadrature sinusoidal oscillators using grounded capacitors,” *International Journal of Electronics*, vol. 100, pp. 259–273, Feb. 2013.

[3] D. Biolek, “CDTA – Building block for current-mode analog signal processing,” in *Proceedings of European Conference on Circuit Theory and Design 2003*, 2003, vol. 3, pp. 397–400.

[4] M. Siripruchyanun and W. Jaikla, “Cascadable current-mode biquad filter and quadrature oscillator using DO-CCCIIs and OTA,” *Circuits*

*Systems and Signal Processing*, vol. 28, pp. 99–110, Feb. 2009.

[5] M. Siripruchyanun and W. Jaikla, "Current-controlled current differencing transconductance amplifier and applications in continuous-time signal processing circuits," *Analog Integrated Circuits and Signal Processing*, vol. 61, pp. 247–257, Dec. 2009.

[6] M. Siripruchyanun, N. Poonnoy, C. Upathamkuekool, and K. Payakkakul, "Square-wave and PWM signal generators based on CCCDTRA," in *Proceedings 39th International Conference on Telecommunications and Signal Processing (TSP)*, 2016, pp. 295–298.

[7] C. Toumazou, F. J. Lidgey, and D. Haigh, *Analogue IC Design: The Current-Mode Approach*. Kentucky: Presbyterian Publishing Corp, 1990.

[8] M. Siripruchyanun and W. Jaikla, "Electronically controllable current-mode universal biquad filter using single DO-CCCDTA," *Circuits Systems and Signal Processing*, vol. 27, pp. 113–122, Jan.–Feb. 2008.

[9] D. Biolek, R. Senani, V. Biolkova, and Z. Kolka, "Active elements for analog signal processing: Classification, review, and new proposals," *Radioengineering*, vol. 17, pp. 15–32, 2008.

[10] J. Xu, C. Wang, and J. Jin, "Current differencing cascaded transconductance amplifier (CDCTA) and its applications on current-mode n$^{th}$-order filters," *Circuits, Systems, and Signal Processing*, vol. 32, pp. 2047–2063, Oct. 2013.

[11] B. Zhu, C. Wang, Y. Sun, and J. Liu, "Systematic design of current-mode multiple-loop feedback filters based on a single CDCTA," *IETE Journal of Research*, vol. 63, pp. 435–447, 2017.

[12] S. Tandee, W. Jaikla, P. Suwanjan, D. Siriphot, and S. Maneewan, "Design of current-mode multiphase sinusoidal oscillators using CDCTA with independent control of CO and FO," in *Proceedings 13th International Symposium on Communications and Information Technologies (ISCIT 2013)*, 2013, pp. 315–319.

[13] C. H. Wang and H. R. Lin, "Multifunction current differencing cascaded transconductance amplifier (MCDCTA) and its application to current-mode multiphase sinusoidal oscillator," *Journal of Electrical Engineering*, vol. 66, no. 5, pp. 241–249, 2015.

[14] J. Jin, "Multi-function current differencing cascaded transconductance amplifier (MCDCTA) and its application to current-mode multiphase sinusoidal oscillator," *Wireless Personal Communications*, vol. 86, pp. 367–383, Jan. 2016.

[15] E. Tlelo-Cuautle, L. G. de la Fraga, K. Phanrattanachai, and K. Pitaksuttayaprot, "CDCTA and OTA realizations of a multi-phase sinusoidal oscillator," *IETE Technical Review*, vol. 32, pp. 497–504, 2015.

[16] A. U. Keskin and D. Biolek, "Current mode quadrature oscillator using current differencing transconductance amplifiers (CDTA)," *IEE Proceedings-Circuits Devices and Systems*, vol. 153, pp. 214–218, Jun. 2006.

[17] D. Biolek, A. Ü. Keskin, and V. Biolkova, "Quadrature oscillator using CDTA-based integrators," *WSEAS Transactions on Electronics*, vol. 3, pp. 463–469, 2006.

[18] W. Tangsrirat, "Current differencing transconductance amplifier-based current-mode four-phase quadrature oscillator," *Indian Journal of Engineering and Materials Sciences*, vol. 14, pp. 289–294, Aug. 2007.

[19] W. Jaikla, M. Siripruchyanun, J. Bajer, and D. Biolek, "A simple current-mode quadrature oscillator using single CDTA," *Radioengineering*, vol. 17, pp. 33–40, Dec. 2008.

[20] A. Lahiri, "Novel voltage/current-mode quadrature oscillator using current differencing transconductance amplifier," *Analog Integrated Circuits and Signal Processing*, vol. 61, pp. 199–203, Nov. 2009.

[21] N. Pandey and S. K. Paul, "Single CDTA-based current mode all-pass filter and its applications," *Journal of Electrical and Computer Engineering*, vol. 2011, pp. 1–5, 2011.

[22] J. Jin and C. H. Wang, "Single CDTA-based current-mode quadrature oscillator," *AEU-International Journal of Electronics and Communications*, vol. 66, pp. 933–936, 2012.

[23] J. Jin and P. Liang, "Resistorless current-mode quadrature oscillator with grounded capacitors," *Revue Roumaine des Sciences Techniques Serie Electrotechnique et Energetique*, vol. 58, pp. 304–313, 2013.

[24] J. Jin and C. H. Wang, "CDTA-based electronically tunable current-mode quadrature oscillator,"

*International Journal of Electronics*, vol. 101, pp. 1086–1095, Aug. 2014.

[25] S. Chen and J. Wang, "Current-mode current-tunable four-phase quadrature oscillator," *Optik - International Journal for Light and Electron Optics*, vol. 125, pp. 6227–6230, 2014.

[26] J. Jin and C. H. Wang, "Current-mode universal filter and quadrature oscillator using CDTAs," *Turkish Journal of Electrical Engineering and Computer Sciences*, vol. 22, pp. 276–286, 2014.

[27] S. Summart, C. Thongsopa, and W. Jaikla, "Dual-output current differencing transconductance amplifiers-based current-mode sinusoidal quadrature oscillators," *Journal of Circuits Systems and Computers*, vol. 23, Jul. 2014.

[28] P. Prommee and F. Khateb, "High-performance current-controlled CDCCC and its applications," *Indian Journal of Pure and Applied Physics*, vol. 52, pp. 708–716, 2014.

[29] J. Jin, "Resistorless active SIMO universal filter and four-phase quadrature oscillator," *Arabian Journal for Science and Engineering*, vol. 39, pp. 3887–3894, May 2014.

[30] Y. Li, C. H. Wang, and S. Q. Chen, "Current-mode four-phase quadrature oscillator," *Revue Roumaine Des Sciences Techniques-Serie Electrotechnique Et Energetique*, vol. 60, pp. 293–301, Jul.–Sep. 2015.

[31] S. Summart, C. Thongsopa, and W. Jaikla, "New current-controlled current-mode sinusoidal quadrature oscillators using CDTAs," *AEU - International Journal of Electronics and Communications*, vol. 69, pp. 62–68, 2015.

[32] L. Cai-hong, "Design of low-power electronically controllable dual-mode third-order quadrature oscillator using single CDCTA-C," *Acta Electronica Sinica*, vol. 45, pp. 599–604, 2017.

[33] R. Keawon and W. Jaikla, "A resistor-less current-mode quadrature sinusoidal oscillator employing single CCCDTA and grounded capacitors," *Przegląd Elektrotechniczny (Electrical Review)*, vol. 8, pp. 138–141, 2011.

[34] D. Frey, "Log-domain filtering: An approach to current-mode filtering," *IEE Proceedings Circuits, Devices and Systems*, vol. 140, pp. 406–416, 1993.