OTA Based Current-Mode Sinusoidal Quadrature Oscillator Circuits

Dattaguru V. Kamath
Department of E&C Engg.,
Manipal Institute of Technology, Manipal University,
Manipal, India
dv.kamath@manipal.edu, reachdvkamath@yahoo.com

***Abstract*—This paper discusses the circuit realization, analysis and design of OTA based current-mode quadrature oscillators. The active building blocks used in the oscillator design are SO-OTA, DO-OTAand/ or MO-OTA. The proposed current-mode oscillator circuitsare derived from integrator based continuous-time filter structures. The proposed oscillator circuits provide sinusoidal output currents with 90º phase difference and other advantages include simplicity, good sensitivity and use of grounded capacitors.The workability of the proposed oscillators is verified with SPICE simulations.**

***IndexTerms*—Analog Signal Processing, Voltage-mode, Current-mode,Sinusoidal oscillator,Quadrature oscillator,Operational Transconductance Amplifier (OTA), SO-OTA, DO-OTA, MO-OTA**

I. INTRODUCTION

The different active building blocks like op-amp, CC, CFOA,OTA, OTRA are used in analog signal processing. Analog filters and oscillators are frequently used in analog and mixed signal circuit design. The OTA based voltage-mode and current-mode continuous-time filters are addressed in the literature[1]-[15].The sinusoidal quadrature oscillators are used in communicationand instrumentation circuits.This paper discusses OTA based voltage-mode/ current-mode oscillator circuits derived from two integrator loop filter structures [1]-[7]. The properties and typical applications of OTA are considered in section II. The block diagram, circuit structure and analysis for proposed OTA based current-mode sinusoidal quadrature oscillators are presented in section III. The analysis of proposed oscillator circuits using finite input and output parasitic conductances and capacitancesofthe OTA is considered in section IV. The section V compares the proposed quadrature oscillator circuits with previously reported circuits. The design methodology and simulation results are presented in section VI.The concluding summary is presented in section VII.

II. OPERATIONAL TRANSCONDUCTANCE AMPLIFIER

An OTA is a versatile analog block having two inputs and a current output.In brief, the OTA is a voltage controlled current source (VCCS). An ideal OTA has infinite input and output impedances and a tunable transconductance. The attractive features of OTA are controllability of its transconductance by adjusting the dc bias current and higher bandwidth. The symbols of SO-OTA (single-output OTA), DO-OTA (dual-output OTA) and MO-OTA (multiple-output OTA) are presented in Fig. 1.The output currents of SO-OTA, DO-OTA and MO-OTA are given by

$$I_o^+ = I_o^- = g_m(V_i^+ - V_i^-) \quad (1)$$

whereI_o^+, I_o^-aredual output currents,$g_m$is the transconductance of the OTA,V_i^+andV_i^-denote non-inverting and inverting input voltages of the OTArespectively.

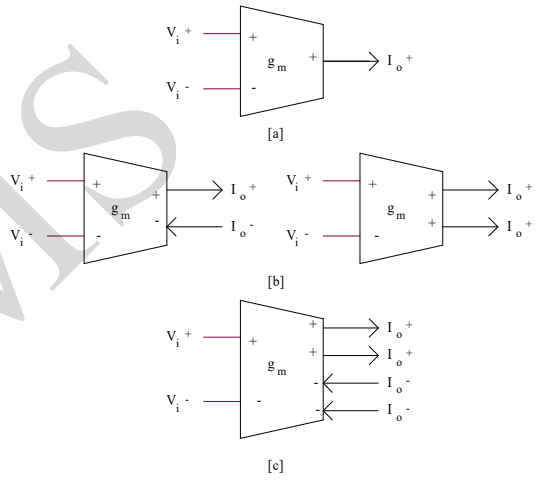


Fig. 1 Circuit symbols of [a] SO-OTA, [b] DO-OTA and [c]MO-OTA

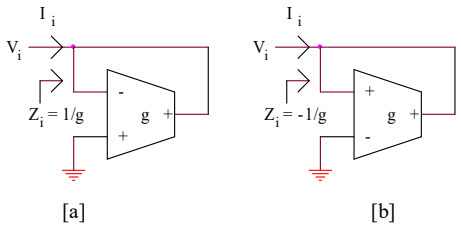


Fig. 2 OTA simulation of voltage-variable resistors: [a] grounded positive resistor, [b] grounded negative resistor

It is shown that the grounded and floating type resistors [2]-[7], [10]-[12] can be simulated using OTAs. The circuit realization of OTA simulated grounded positive and negative resistor is presented in Fig. 2.The OTA based voltage-mode and current-mode integrator circuits [4]-[6], [8] areshown in Fig. 3 and 4 respectively.

IJSMS

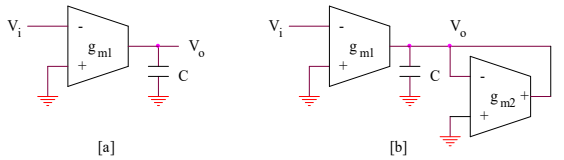


Fig. 3 OTA based voltage-mode integrators: (a) lossless, (b) lossy

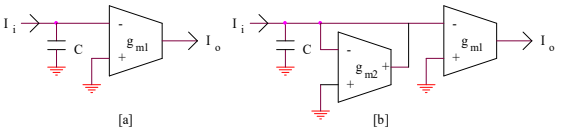


Fig. 4 OTA based current-mode integrators: (a) lossless, (b) lossy

The transfer function of OTA based voltage-mode lossless and lossyintegrators in Fig. 3 are respectively shown to be

$$V_o/V_i = -(g_{m1}/sC) \quad (2.1a)$$

$$V_o/V_i = -g_{m1}/(g_{m2} + sC) \quad (2.1b)$$

The transfer function of OTA based current-mode lossless and lossy integrators in Fig. 4 are respectively shown to be

$$I_o/I_i = -(g_{m1}/sC) \quad (2.2a)$$

$$I_o/I_i = -g_{m1}/(g_{m2} + sC) \quad (2.2b)$$

III. OTABASED CURRENT-MODESINUSOIDAL QUADRATURE OSCILLATORS

This section discusses theproposed OTA based current-mode sinusoidal quadrature oscillator circuits.

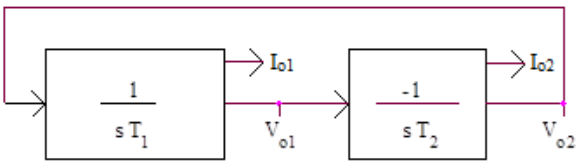
A. DO-OTAbased current-mode/voltage-mode quadrature oscillatorusing lossless integrators alone

The OTA-based quadrature oscillatorcircuit in Fig. 5 [b] based on two-integrator loop structure (refer Fig. 5 [a]) employs two OTAs and two grounded capacitors. Generally single outputOTAs(SO-OTAs) are sufficient to obtain voltage output signals. Dual output OTAs (DO-OTAs) are needed to provide current output signals. By routine analysis, the characteristic equation and frequency of oscillation (FO)for circuit in Fig. 5[b] are shown to be

$$s^2C_1C_2 + g_1g_2 = 0 \quad (3.1a)$$

$$\omega_o = \sqrt{g_1g_2/C_1C_2} \quad (3.1b)$$

This oscillator circuit has no independent control on the oscillation condition. This disadvantage is overcome by using one lossy integrator in the two integrator loop.



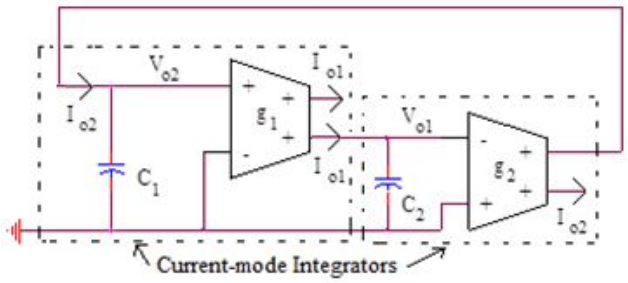


Fig. 5 [a] Generalized block diagram of quadrature oscillator based on two integrator loop filter structure without damping, [b] DO-OTA based current-mode/ voltage-mode sinusoidal oscillator circuit derived from [a]

B. DO-OTAbased current-mode/ voltage-mode quadrature oscillator using lossy and lossless integrators

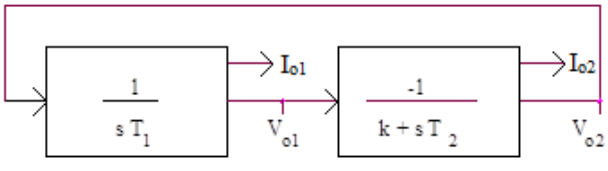
The generalized block diagram of a sinusoidal oscillator based on Tow-Thomas biquad filter structure [2]-[6], [13], a special case of two integrator loop configuration is shown inFig. 6[a].The DO-OTA based current-mode/voltage-mode sinusoidal quadrature oscillator circuit derived fromTow-Thomas biquad filter structureis given in Fig. 6[b].The characteristic equation, condition of oscillation (CO) and the frequency of oscillation (FO)of DO-OTA basedquadrature oscillatorin Fig. 6[b] are respectively shown to be

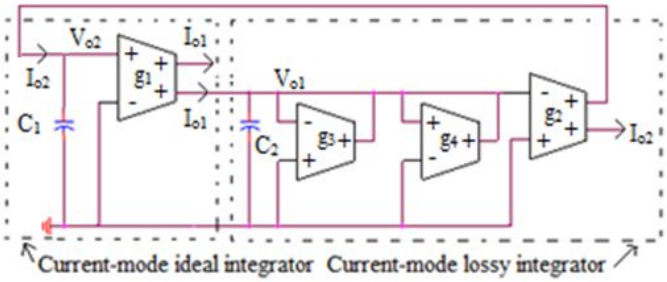
$$s^2C_1C_2 + sC_1(g_3 - g_4) + g_1g_2 = 0 \quad (3.2a)$$

$$g_3 = g_4 \quad (3.2b)$$

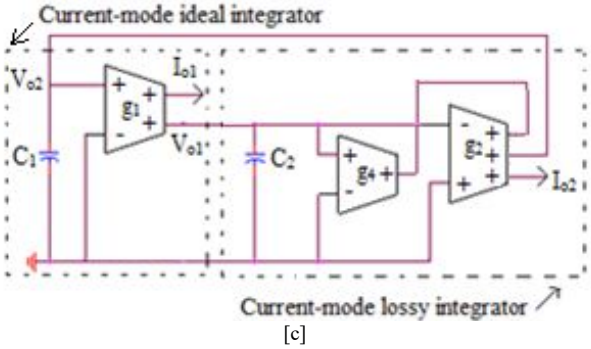
$$\omega_o = \sqrt{g_1g_2/C_1C_2} \quad (3.2c)$$

An improved quadrature oscillator circuit derived from Fig. 6(b) is presented in Fig. 6(c). It can be seen that this oscillator oscillates at the same frequency of oscillation (FO) given in (3.2c) under the condition $g_2 = g_4$.Forboth quadrature oscillator circuits in Fig. 6[b] and [c], the condition of oscillation is satisfied without affecting the frequency of oscillation and vice versa.





IJSMS



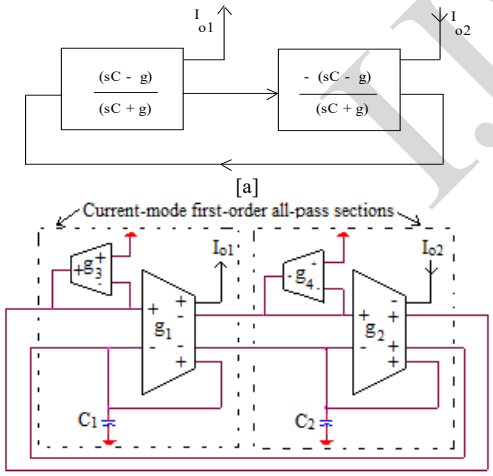
[c]

Fig. 6[a] Generalized block diagram of quadrature oscillator based on Tow-Thomas biquad filter structure,[b] DO-OTA based current-mode/voltage-mode quadrature oscillator circuit derived from [a],[c] Alternate quadrature oscillator circuit derived from [b]

It is well known that quadrature oscillator is realizable using first-order all-pass filter sections. The realization of current-mode OTA-C first-order all-pass filter circuits have been extensively researched [10]-[12]. The quadrature oscillators using CC/ CDTA based first-order all-pass filtersectionsare discussed in literature [24], [25]. The generalized block diagram and OTA-C implementationof quadrature oscillatorusing first-order all-pass filter sections [10], [11] is reproduced here in Fig. 7 [a]-[b] for comparative study.In the block diagram of Fig. 7 [a], note that first block is non-inverting type first-order all-pass filter and the second block is inverting type, both having unity gain.It can be shown that the circuit in Fig. 7[b] oscillates unconditionally at a frequency given by

$$\omega_o = \sqrt{g_{1,3}\, g_{2,4}/C_1C_2} \qquad (3.3)$$

where$g_{1,3} = g_1 = g_3; g_{2,4} = g_2 = g_4andC_1 = C_2 = C$.



[b]

Fig. 7[a] Generalized block diagram of quadrature oscillator using first-order all-pass filter sections and [b] OTA-C implementation using first-order all-pass networks

The performance measures like characteristic equation, condition of oscillation (CO), frequency of oscillation (FO) and sensitivity of the oscillation frequency with respect to component values for the current-mode sinusoidal quadrature oscillator circuits in Fig. 5[b], Fig. 6[b]-[c], Fig. 7[b] are summarized in Table I.

Table I. Summary of Performance Measures for Different Quadrature Oscillator Circuits

Circuit	Characteristic equation of oscillator	Condition of Oscillation (CO)	Frequency of oscillation ω_o(FO)	Sensitivity of oscillator frequency
Fig. 5(b)	$s^2C_1C_2 + g_1g_2 = 0$	No	$\sqrt{\frac{g_1g_2}{C_1C_2}}$	$S^{\omega_o}_{g_1,g_2} = -S^{\omega_o}_{C_1,C_2} = 0.5$
Fig. 6(b)	$s^2C_1C_2 + sC_1(g_3 - g_4) + g_1g_2 = 0$	$g_3 = g_4$	$\sqrt{\frac{g_1g_2}{C_1C_2}}$	$S^{\omega_o}_{g_1,g_2} = -S^{\omega_o}_{C_1,C_2} = 0.5$
Fig. 6(c)	$s^2C_1C_2 + sC_1(g_2 - g_4) + g_1g_2 = 0$	$g_2 = g_4$	$\sqrt{\frac{g_1g_2}{C_1C_2}}$	$S^{\omega_o}_{g_1,g_2} = -S^{\omega_o}_{C_1,C_2} = 0.5$
Fig. 7(b)	$s^2C_1C_2 + g_{1,3}g_{2,4} = 0$	No	$\sqrt{\frac{g_{1,3}g_{2,4}}{C_1C_2}}$	$S^{\omega_o}_{g_{1,3},g_{2,4}} = -S^{\omega_o}_{C_1,C_2} = 0.5$

IV. EFFECT OF OTA NON-IDEALITIES

In this section, we consider the effect of OTA non-idealities viz., finite input and output conductances and capacitancesof the OTAs on the characteristic equationof the proposed oscillators. The simplified non-ideal macro model of OTA used for analysis is shown in Fig. 8.

IJSMS

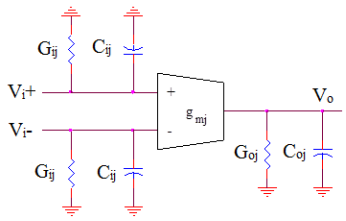


Fig. 8 Non-ideal OTA macro-model

Denoting the finite input andoutput conductances of the OTAs as G_{ij}, $G_{oj}$and capacitances as C_{ij}, C_{oj} forj = 1, 2 for thej^{th} OTAand denoting$G_1' = G_{o1} + G_{i2}$, $G_2' = G_{o2} + G_{i1}$, $C_1' = C_1 + C_{o2} + C_{i1}$and $C_2' = C_2 + C_{o1} + C_{i2}$, the resulting characteristic equationfor the circuit of Fig. 5[b] can be derived as

$$s^2C_1'C_2' + s\{G_1'C_1' + G_2'C_2'\} + g_1g_2 + G_1'G_2' = 0 \quad (3.4a)$$

From (3.4a) the coefficient of the s-term is negligibly small at low frequencies and the perturbed value of oscillation frequency due to OTA parasitics is shown to be

$$\omega_o' = \sqrt{\left(g_1g_2 + G_1'G_2'\right)/C_1'C_2'} \quad (3.4b)$$

Similarly the non-ideal characteristic equation, condition of oscillation (CO) andfrequency of oscillation (FO) for the current-mode/ voltage-mode quadrature oscillator circuit in Fig. 6 [b] are shown to be

$$s^2C_1^*C_2^* + s\{(g_3 - g_4 + G_2^*)C_1^* + G_1^*C_2^*\} + g_1g_2 + (g_3 - g_4)G_1^* + G_1^*G_2^* = 0 \quad (3.5a)$$

$$g_4 = g_3 + G_2^* + G_1^*(C_2^*/C_1^*) \quad (3.5b)$$

$$\omega_o^* = \sqrt{(g_1g_2 + G_1^*G_2^*)/C_1^*C_2^*} \quad (3.5c)$$

where

$$G_1^* = G_{o2} + G_{i1},\ G_2^* = G_{o1} + G_{o3} + G_{o4} + G_{i2} + G_{i3} + G_{i4}$$

$$C_1^* = C_1 + C_{o2} + C_{i1},$$

$$C_2^* = C_2 + C_{o1} + C_{o3} + C_{o4} + C_{i2} + C_{i3} + C_{i4}$$

V. COMPARISON OF VARIOUS QUADRATURE OSCILLATOR CIRCUITS

In this section, the current-mode OTA-C quadrature oscillator circuits presented are compared with some of the previously reported OTA based oscillators in the literature. TableII compares different oscillator circuits with respect to number of OTAs, number of extra OTA outputs, independent controllability of condition of oscillation (CO) etc.

Table Ii Comparison of Various Ota-C Sinusoidal Oscillators

Ref./ Fig.	Output type	No. of OTAs	No. of extra OTA outputs	No./type of capacitors used	Independent control on oscillation condition (CO)
[16]Fig. 5[a]	VM	3	0	2grounded	Yes
[16]Fig. 5[b]	VM	4	0	2grounded	Yes
[17]Fig. 2	VM	3	0	2 grounded	No
[21] Fig. 2	CM	4	4	2grounded	Yes
[19] Fig. 1[Circuit (1), (2), (3), (5)]	CM	3	4	2 grounded	Yes
[19]Fig. 1 [Circuit (4)]	CM	3	3	2grounded	No
This paper Fig. 5[b]	VM/ CM	2	2	2grounded	No
This paper Fig. 6[b]	VM/ CM	4	2	2 grounded	Yes
This paper Fig. 6[c]	VM/ CM	3	3	2 grounded	Yes
[10],[11] and this paper Fig. 7[b]	CM	4	6	2 grounded	No

VM: voltage-mode; CM: current-mode

VI. SIMULATION RESULTS

The proposed DO-OTA basedcurrent-mode sinusoidalquadrature oscillators in Fig. 5[b] and Fig. 6[b] have been simulated using SPICE based TINA circuit simulator. The model parameters, device dimensions and supply voltages used in simulation are given in Table III.The schematic circuits of SO-OTA, DO-OTA [10]-[14] and TO-OTA [15] are presented in Fig. 9. The sinusoidal waveforms obtained for quadrature oscillator circuits in Fig. 5[b] and Fig. 6[b] are presented in Fig. 10 and Fig. 11 respectively.

Table Iii: Simulation Details

Model parameters used	Level 7BSIM3 0.5 µm
Aspect ratios for NMOS and PMOS transistor	W = 4 µm, L = 2 µm
Supply voltages	V_{dd}= +2V,V_{ss} = -2V

The frequency of oscillation depends on transconductance and capacitance values. The*equal transconductance*and/ or*equal capacitance* approach is chosen to design quadrature oscillators. The transconductance of OTAs are tuned by varying bias currents. As the transconductance values of OTAs are affected by second and higher order effects, they were computed by dc simulation. The design values of transconductor and capacitors used in the simulations along with the theoretical and practical output frequency and percentage of error for the proposed circuits are summarized in Table IV.

IJSMS

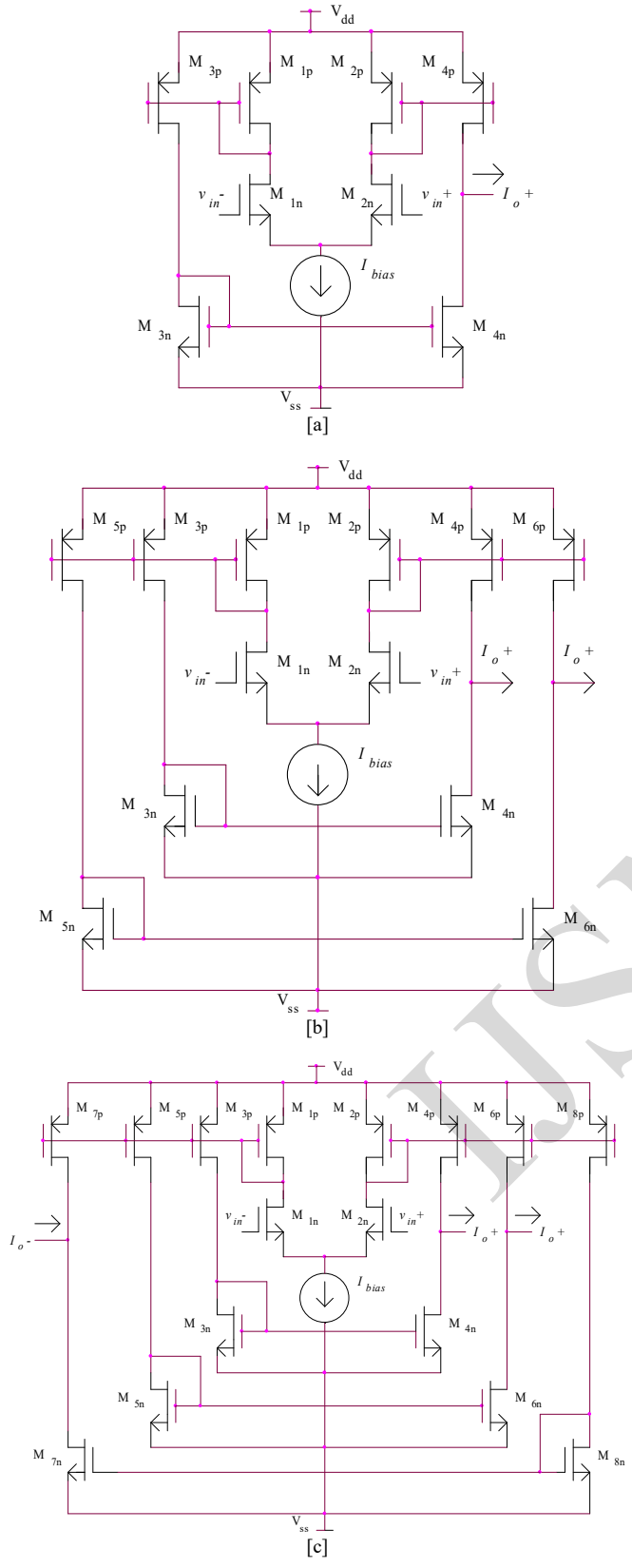


Fig. 9 CMOS schematic circuit of (a) SO-OTA (b) DO-OTA and (c) TO-OTA

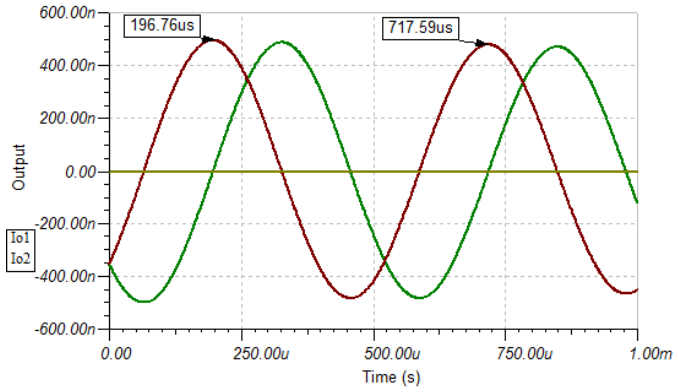


Fig. 10Simulated output current waveforms I_{o1}, $I_{o2}$of DO-OTA based sinusoidal oscillator circuit of Fig. 5 [b]

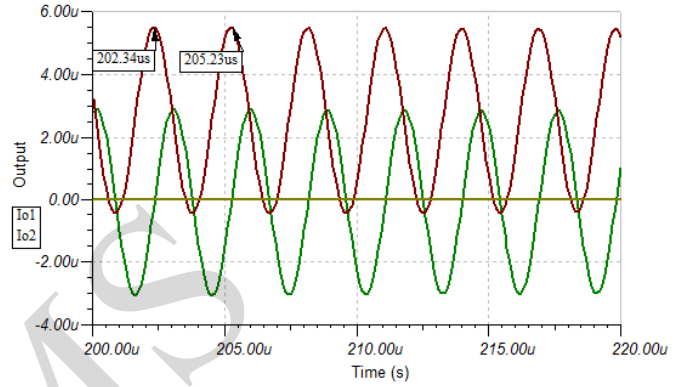


Fig. 11Simulated output current waveforms I_{o1}, $I_{o2}$of DO-OTA based sinusoidal oscillator circuit of Fig. 6 [b]

Table iv: Values of the Capacitors and Transconductances for Various Oscillators

Circuit	$g_{m1,2}$ [$I_{bias1,2}$]	$g_{m3,4}$ [$I_{bias3,4}$]	$C_{1,2}$	f_o (theoretical)	f_o (practical)	% of error
Fig. 5 [b]	56.55 µs [10 µA]	----	5 nF	1.8 kHz	1.92 kHz	-6.66
Fig. 6 [b]	105.538 µs [100uA]	105.538 µs [100uA]	50 pF	335.94 kHz	346.02 kHz	-3

VII. CONCLUSION

The transistor level circuit simulations were performed for the proposed OTA based sinusoidal oscillators and the simulation results are in good agreement with theory. The

IJSMS

OTA-based quadrature oscillatorcircuits in Fig. 5[b] and 7[b] have no independent control on the oscillation condition (CO). The quadrature oscillatorcircuitsin Fig. 6[b], 6[c]using lossless as well lossy integrator provide independenttunability of the frequency of oscillation (FO).All the proposed oscillators use grounded capacitors.

REFERENCES

[1] S. Sedra and P. O. Brackett, Filter Theory and Design: Active and Passive, Matrix Series in Circuits and Systems, Matrix Publishers, 1978.

[2] R. Schaumann, M. S. Ghausi, K. R. Laker, Design of analog filters: passive, active RC and switched capacitor, Prentice-Hall, Englewood cliffs, New Jersey, 1981.

[3] Toumazou, F. D. Lidgey, and D. G. Haigh, Analog IC Design: The Current Mode Approach. London, U.K.: Peregrinus, 1990.

[4] T. Deliyannis, Y. Sun, and J. K. Fidler, Continuous-Time Active Filter Design, CRC Press, Florida, U.S.A, 1999.

[5] P. V. Ananda Mohan, Current-Mode VLSI Analog Filters: Design and Applications, Birkhäuser Boston, 2003.

[6] P. V. Ananda Mohan, VLSI Analog Filters: Active RC, OTA-C, and SC, Birkhäuser Boston, 2013.

[7] R. L. Geiger and E. Sanchez-Sinencio, "Active filter design using operational transconductance amplifiers: a tutorial," IEEE Circuit and Devices Magazine, vol. 1, pp. 20-32, 1985.

[8] Dattaguru V. Kamath, "Overview of Opamp and OTA based Integrators," International Journal of Innovative Research in Electrical, Electronics, Instrumentation and Control Engineering (IJIREEICE), vol. 3, no. 9, pp. 74-81, Sept. 2015.

[9] T. Tsukutani, Y. Sumi, and Y. Fukui, "Electronically tunable current-mode OTA-C biquad using two-integrator loop structure," Frequenz, vol. 60, pp. 53-56, 2006.

[10] Dattaguru V. Kamat, P.V. Ananda Mohan and K. GopalakrishnaPrabhu, "Novel First-order and Second-Order Current-mode filters using Dual-output OTAs and Grounded Capacitors," IEEE Asia Pacific Region 10 (TENCON) Conference held at Hyderabad, India, IEEEXplore, pp. 1-6, 19-21, Nov. 2008.

[11] Dattaguru V. Kamath, P. V. Anandamohan and K. GopalkrishnaPrabhu, "Novel first order and second order current-mode filters using multiple output operational transconsuctance amplifiers," Circuits, Systems, and Signal Processing, Birkhäuser Boston Publishers, vol. 29, no. 3, pp. 553-576, June 2010.

[12] Dattaguru V. Kamat, P. V. Ananda Mohan and K. GopalakrishnaPrabhu, "Current-mode operational transconductance amplifier-capacitor biquad filter structures based on Tarmy–Ghausi Active-RC filter and second-order digital all-pass filters," IET Circuits, Devices and Systems, vol. 4, no. 4, pp. 346-364, July 2010.

[13] Dattaguru V. Kamat, P. V. Ananda Mohan and K. GopalakrishnaPrabhu, "Active-RC filters using two-stage OTAs with and without feed-forward compensation," IET Circuits, Devices and Systems, vol. 5, no. 6, pp. 527-535, Nov 2011.

[14] Dattaguru V. Kamath, "New OTA-C Current-ModeSecond-Order Filters," IIE International Conference on Innovative Engineering Technologies (ICIET 2014) held at Bangkok, Thailand, pp. 137-143, 28-29 Dec. 2014.

[15] Dattaguru V. Kamath, "TO-OTA based current-mode biquad filters," Transactions on Engineering and Sciences, vol. 2, no. 8, pp. 15-26, August 2014.

[16] Rodríguez-Vázquez, A., Linares-Barranco, B., Huertas, J. L. and Sánchez-Sinencio, E., "On the design of voltage-controlled sinusoidal oscillators using OTAs," IEEE Transactions on Circuits and Systems, vol. 37, no. 2, pp.198-211, Feb. 1990.

[17] Raj Senani, M. P. Tripathi, D. R. Bhaskar and B. Amit Kumar, "Systematic Generation of OTA-C Sinusoidal Oscillators," Electronics Letters, IEE (UK), vol. 26, no. 18, pp. 1457-1459, 1990.

[18] Ahmed M. Soliman, "Current conveyor based or unity gain cells based two integrator loop oscillators,"Microelectronics Journal, vol. 42, no. 2, pp. 239-246, Feb. 2011.

[19] Bhaskar, Data Ram, KasimKaramAbdalla, and Raj Senani, "Electronically-controlled current-mode second order sinusoidal oscillators using MO-OTAs and grounded capacitors," Circuits and Systems, vol. 2, no. 2, pp. 65-73, 2011.

[20] Duangmalai, Danupat, and WinaiJaikla, "Realization of current-mode quadrature oscillator based on third order technique," ACEEE International Journal on Electrical and Power Engineering, vol. 2, no. 3, pp. 46-49, Nov 2011.

[21] SaksitSummart, ChanchaiThongsopa, WinaiJaikla, "OTA Based Current-mode Sinusoidal Quadrature Oscillator with Non-interactive Control,"PrzegladElektrotechniczny (Electrical Review), pp.14-17, July 2012.

[22] Wang, H.-Y.; Tran, H.-D.; Nguyen, Q.-M.; Yin, L.-T.; Liu, C.-Y., "Derivation of Oscillators from Biquadratic Band Pass Filters Using Circuit Transformations," Appl. Sci., vol. 4, no. 4, pp. 482-492, 2014.

[23] Summart, S., "CCCIIs-based sinusoidal quadrature oscillators with non-interactive control of condition and frequency," Indian Journal of Pure & Applied Physics (IJPAP), vol. 52, no.4, pp.277-283, 2015.

[24] Horng, Jiun-Wei., "Current conveyors based all-pass filters and quadrature oscillators employing grounded capacitors and resistors," Computers & Electrical Engineering, vol. 31, no. 1, pp. 81-92, 2005.

[25] Pandey, N., Paul, S. K.,"Single CDTA-based current mode all-pass filter and its applications," Journal of Electrical and Computer Engineering,Volume 2011,Article ID 897631, 5 pages, 2011.

IJSMS