American Journal of Electrical and Electronic Engineering, 2017, Vol. 5, No. 6, 202-206
Available online at http://pubs.sciepub.com/ajeee/5/6/2

DOI:10.12691/ajeee-5-6-2

CMOS-Compatible Linear VCO Using a Single CFOA and Grounded Capacitors

D. K. Srivastava[1], V. K. Singh[2], R. Senani[3,*]

[1]Department of Electronics and Communication Engineering, SR Institute of Management and Technology, Lucknow, India
[2]Department of Electronics Engineering, Institute of Engineering and Technology, Sitapur Road, Aliganj, Lucknow, India
[3]Division of Electronics and Communication Engineering, Netaji Subhas Institute of Technology, Sector 3, Dwarka, New Delhi, India
*Corresponding author: senani@ieee.org

Abstract A simple CMOS-compatible *linear* voltage controlled oscillator (VCO) has been presented which employs a single CFOA, four MOSFETs and three grounded capacitors as preferred for IC implementation. In the proposed circuit, variable frequency oscillations are obtained by simultaneous variation of two voltage-controlled-resistors in the circuit which appear in the expression for oscillation frequency in the product form but appear as a ratio in the condition of oscillation (which therefore, remains unaffected).The workability of the proposed VCO has been confirmed by SPICE simulations using an exemplary CMOS CFOA and CMOS VCRs both implementable in 0.18μm CMOS technology.

Keywords: *sinusoidal oscillators, current feedback operational amplifiers, voltage controlled oscillators, voltage controlled resistance*

Cite This Article: D. K. Srivastava, V. K. Singh, and R. Senani, "CMOS-Compatible Linear VCO Using a Single CFOA and Grounded Capacitors." *American Journal of Electrical and Electronic Engineering*, vol. 5, no. 6 (2017): 202-206. doi: 10.12691/ajeee-5-6-2.

1. Introduction

Analog signal processing/signal generation circuits based on the current feedback operational amplifiers (CFOA) are suitable for high frequency applications as compared to conventional op-amps because of the several advantages offered by them, such as- (i) wider and nearly constant bandwidth independent of gain (for low /medium gains) (ii) higher slew rates (typically 2000V/μsec) and (iii) requirement of a smaller number of external passive components to perform a specified function. A large number of sinusoidal oscillator circuits using CFOAs have been evolved so far, for instance, see [3,5-8,10-12,15,17-20,24-25]. While a wide variety of bipolar CFOAs are available as off-the-shelf ICs, on the other hand, several CMOS-based CFOA topologies have also been introduced in the literature, for instance, see [24] and the references cited therein.

The main object of this communication is to introduce a simple voltage-controlled-oscillator (VCO) in which the frequency of oscillation can be varied linearly by simultaneously changing two voltage-controlled-resistances (VCR) in the circuit through an external control voltage V_C. These resistors feature in the expression for the condition of oscillation (CO) as a ratio but appear in the frequency of oscillation (FO) as a product. Thus, when these two resistors are replaced by two CMOS VCRs derived by a common external voltage V_C, a *linear* control of the FO results.

2. The Proposed Configuration

The CFOA is a four-port active building block which is characterized by the following hybrid matrix:

$$\begin{bmatrix} i_y \\ v_x \\ i_z \\ v_w \end{bmatrix} = \begin{bmatrix} 0 & 0 & 0 & 0 \\ 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \end{bmatrix} \begin{bmatrix} v_y \\ i_x \\ v_z \end{bmatrix}. \quad (1)$$

The proposed configuration is shown in Figure 1 which requires only a single CFOA, four MOSFETs and three grounded capacitors with no passive resistors, as preferred for IC implementation [25,26,27,28].

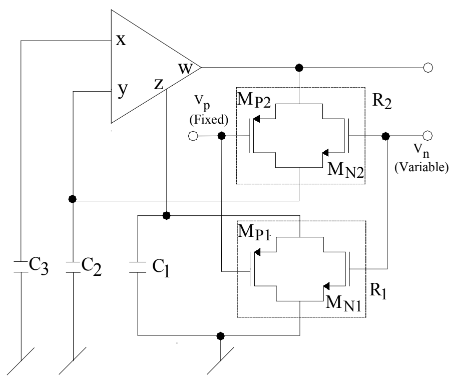

Figure 1. The proposed Linear VCO

By a straight forward analysis, the condition of oscillation (CO) and the frequency of oscillation (FO) of the circuit are found to be:

$$C_3 = \left(\frac{R_2}{R_1}\right) C_2 + C_1 \qquad (2)$$

$$f = \frac{1}{2\pi}\sqrt{\frac{1}{R_1 R_2 C_1 C_2}}. \qquad (3)$$

Note that the resistors R_2 and R_1 appear as ratio in the CO but as product in FO. Thus, if these resistances are varied *simultaneously and equally,* CO will remain unaffected but oscillation frequency can be varied. Accordingly, these resistor pairs are replaced by two identical CMOS VCRs [1,16] derived by a common external control voltage V_C as shown. The equivalent resistance simulated by each VCR circuit is given by

$$R_{\mathbf{eqi}} = \frac{\left(\mathbf{V}_1 - \mathbf{V}_2\right)}{\mathbf{I}} = \frac{1}{K_0\left(\mathbf{V_{ni}} - \mathbf{V_{pi}} - \mathbf{V_{tni}} + \mathbf{V_{tpi}}\right)}; i = 1,2 \qquad (4)$$

where, K_0 is the trans-conductance parameter and V_{Tpi} and V_{Tni} are the threshold voltages of the i^{th} PMOS and i^{th} NMOS transistors respectively. If we choose $R_1=R_2=R$ or $R_{eq1}=R_{eq2}=R_{eq}$ with both of these replaced by two identical VCR circuits derived by common control voltages V_{ni} and V_{pi}, as shown, the eqn. (2) for FO would be modified as:

$$f_0 = \frac{K_0\left(\mathbf{V_n} - \mathbf{V_p} - \mathbf{V_{tn}} + \mathbf{V_{tp}}\right)}{2\pi\sqrt{C_1 C_2}}. \qquad (5)$$

Therefore, it is clear that oscillation frequency has now become a *linear* function of one of the common control voltages V_{ni} or V_{pi} (keeping V_{pi} fixed and V_{ni} variable or vice-versa) and the circuit, thus, realizes a *linear* VCO.

3. Effect of the Parasitic Impedances of the CFOA

Considering the various parasitic impedances of the CFOA, namely, the finite non-zero input resistance R_x at port x, the non-infinite input impedance consisting of $R_y \| \frac{1}{SC_y}$ at port y and the non-infinite output impedance consisting of $R_z \| \frac{1}{SC_z}$ at port z, the non-ideal characteristic equation (CE) of the proposed circuit is found to be

$$a_3 s^3 + a_2 s^2 + a_1 s + a_0 = 0 \qquad (6)$$

where

$$a_3 = R_x\left[(C_1C_2C_3 + C_1C_3C_y + C_3C_yC_z + C_2C_3C_z)\right]$$

$$a_2 = \left[\begin{array}{l} (C_1C_2 + C_1C_y + C_yC_z + C_2C_z) + \\ R_x\left\{\begin{array}{l}\left(\frac{C_1C_3 + C_2C_3 + C_3C_y}{R_1}\right) + \left(\frac{C_3C_z}{R_2}\right) \\ + \left(\frac{C_1C_3 + C_3C_z}{R_y}\right) + \left(\frac{C_2C_3 + C_3C_y}{R_z}\right)\end{array}\right\}\end{array}\right]$$

$$a_1 = \left[\begin{array}{l}\left(\frac{C_2}{R_1} + \frac{C_1}{R_2} - \frac{C_3}{R_2}\right) \\ + \left(\frac{C_1}{R_y} + \frac{C_2}{R_z} + \frac{C_y}{R_1} + \frac{C_y}{R_z} + \frac{C_z}{R_2} + \frac{C_z}{R_2}\right) \\ + R_x\left(\frac{C_3}{R_1R_2} + \frac{C_3}{R_1R_y} + \frac{C_3}{R_2R_z} + \frac{C_3}{R_yR_z}\right)\end{array}\right]$$

$$a_0 = \left[\left(\frac{1}{R_1R_2} + \frac{1}{R_1R_y} + \frac{1}{R_yR_z} + \frac{1}{R_2R_z}\right)\right].$$

From the above, the non-ideal expression for the CO is found to be

$$C_3 = \left[\frac{\left\{\begin{array}{l}\frac{C_2}{R_1} + \frac{C_1}{R_2} + \frac{C_1}{R_y} + \frac{C_2}{R_z} \\ + \frac{C_y}{R_1} + \frac{C_y}{R_z} + \frac{C_z}{R_y} + \frac{C_z}{R_2}\end{array}\right\}}{\left\{\begin{array}{l}\frac{1}{R_2} + R_x\omega_0\left(C_1C_2 + C_1C_y + C_yC_z + C_2C_z\right) \\ - R_x\left(\frac{1}{R_1R_2} + \frac{1}{R_1R_y} + \frac{1}{R_2R_z} + \frac{1}{R_yR_z}\right)\end{array}\right\}}\right] \qquad (7)$$

whereas the non-ideal expression for the FO is found to be

$$\omega_{0N.Ideal} = \omega_{0ideal}\sqrt{\frac{\left[\left(1 + \frac{R_1R_2}{R_yR_z} + \frac{R_1R_2}{R_1R_y} + \frac{R_1R_2}{R_2R_z}\right)\right]}{\left[\begin{array}{l}\left\{1 + \frac{C_2C_z}{C_1C_2} + \frac{C_yC_z}{C_1C_2} + \frac{C_1C_y}{C_1C_2}\right\} \\ + \frac{R_x}{C_1C_2}\left\{\begin{array}{l}\left(\frac{C_2C_3 + C_3C_y}{R_1}\right) \\ + \left(\frac{C_1C_3 + C_3C_z}{R_2}\right) \\ + \left(\frac{C_1C_3 + C_3C_z}{R_y}\right) \\ + \left(\frac{C_2C_3 + C_3C_y}{R_z}\right)\end{array}\right\}\end{array}\right]}} \qquad (8)$$

where,

$$\omega_{0ideal} = \sqrt{\frac{1}{R_1R_2C_1C_2}}. \qquad (9)$$

For the designed values of the components as shown in the next section and taking the parasitic components of the CFOA as $R_x = 50\Omega$, $R_y = 2M\Omega$, $C_y = 2pF$, $R_p = 3M\Omega$, $C_p = 4.5pF$, it is found that the non-ideal CO is not affected significantly due to the consideration of the various parasitics. On the other hand, in view of the complex formula for the non-ideal FO, it is difficult to draw any qualitative inference from it. However, the simulation results of the oscillator show that their influence also is not very substantial since the frequency obtained from simulations was found to be 7.13MHz which is very close to the value 7.18 MHz calculated from the ideal formula, which, therefore, implies an error of only -0.0069%.

It is worth mentioning that in the literature on CFOA-based circuits, several researchers have conjectured that having a capacitor at x-port may lead to instability in some cases. We now show that this is not true in the present case. In order to check the stability of the circuit, we apply the Routh-Hurwitz criterion for which, the Routh array is constructed as in Table 1.

Table 1. Routh array from the CE of equation (6)

S^3	a_3	a_1
S^2	a_2	a_0
S^1	$\frac{a_1 a_2 - a_0 a_3}{a_2}$	0
S^0	a_0	0

Therefore, it is clear that there is not any root of the non-ideal characteristic equation in the right half of the s-plane other than the pair of complex conjugate roots which are responsible for generating sinusoidal signals and therefore, are required to be slightly in the right half of the s-plane initially (and eventually movable to the ±jω axis). This will happen if

$$a_1 - \frac{a_0}{a_2} a_3 \le 0 \qquad (10)$$

which implies that

$$C_3 \le \frac{\left(\frac{C_2}{R_1} + \frac{C_1}{R_2} + \frac{C_1}{R_y} + \frac{C_2}{R_z} + \frac{C_y}{R_1} + \frac{C_y}{R_z} + \frac{C_z}{R_y} + \frac{C_z}{R_2}\right)}{\left(\frac{1}{R_2} + R_x \omega_0 \left(C_1 C_2 + C_1 C_y + C_y C_z + C_2 C_z\right) - R_x \left(\frac{1}{R_1 R_2} + \frac{1}{R_1 R_y} + \frac{1}{R_2 R_z} + \frac{1}{R_y R_z}\right)\right)}. \qquad (11)$$

Thus, eqn. (11) should be regarded as the more practicable form of the CO as compared to eqn. (7). It is, therefore, concluded that if the non-ideal CO of the equation (11) is satisfied then there is no other pole which may be located in the right half of the s-plane and thus, the stability of the circuit is also ensured.

4. Completely-CMOS Version of the VCO and SPICE Simulation Results

For realizing a linear VCO implementable in CMOS Technology, the CFOA too needs to be realized in CMOS for which a number of alternatives have been proposed in the recent literature. For the present work, we have chosen the CMOS CFOA employed in [19] (which was derived by extracting a CCII+ from the CMOS DDCC of [16] and then appending a CMOS voltage follower to it) which is reproduced here in Figure 2.

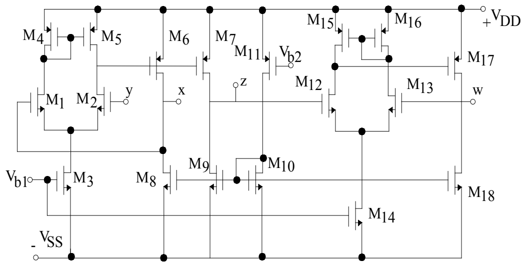

Figure 2. An exemplary CMOS CFOA

Table 2. Aspect Ratios of MOSFETs in the CMOS CFOA

Type of MOSFET	MOSFETs	W (μm)	L (μm)
PMOS	M_4 –M_7, M_{11},M_{15}-M_{17}	10.8	0.54
NMOS	M_1, M_2, M_3, M_8-M_{10}, M_{12}-M_{14},M_{18}	8.1	0.54

Table 3. W/L Ratios of the MOSFETs in CMOS VCR

Type of MOSFET	W (μm)	L (μm)
PMOS	2.5	0.18
NMOS	0.15	0.18

Table 4. Level 7 SPICE parameters for 0.18μm CMOS process

.MODEL CMOSP PMOS (LEVEL = 7 VERSION=3.1 TNOM=27 +TOX=4E-9 XJ=1E-7 K3=0 NCH=4.1589E17 VTH0=-0.37080 +K1=0.5895473 K2=0.0235946 CF=0 CIT=0 A2=0.3 W0=1E-6 +K3B=13.8642028 NLX=1.517201E-7 DVT0W=0 XL=0 DVT1W=0 +DVT2W=0 UC= -1E-10 DVT0=0.7885088 DVT1= 0.2564577 +DVT2=0.1 U0=103.0478426 UA=1.049312E-9 UB=2.545758E-21 +VSAT=1.645114E5 A0=1.627879 AGS=0.3295499 WL=0 WR=1 +B0=5.207699E7 B=1.370868E-6 KETA=0.0296157 A1=0.4449009 +XW=-1E-8 RDSW=306.5789827 PRWG=0.5 PRT=0 PRWB=0.5 +WINT=0 WWN=1 LINT=2.761033E-8 NFACTOR=2 CDSCD=0 +DWG=-2.433889E-8 DWB=-9.34648E-11 LL=0 VOFF=-0.0867009 +RSH=7.5 CDSC=2.4E-4 UTE=-1.5 CDSCB=0 ETA0=1.018318E-3 +ETAB=-3.206319E-4 KT1=-0.11 KT1L=0 DSUB=1.094521E3 +PBSWG=0.8 PCLM=1.3281073 WW=0 PDIBLC1=2.394169E-3 +PSCBE2=5E-10 DROUT=0 PDIBLC2=-3.255915E-6 KT2=0.022 +PDIBLCB=-1E-3 PSCBE1=4.881933E10 WWL=0 DELTA=0.01 +PVAG=2.0932623 MOBMOD=1 LLN=1 UA1=4.31E-9 LWN=1 +UB1=-7.61E-18 UC1=-5.6E-11 LW=0 XPART=0.5 WL=0 +AT=3.3E4 MJSWG=0.3550788 L CAPMOD=2 PB=0.8444261 +CGDO=6.52E-10 CGSO=6.52E-10 PBSW=0.8 CGBO=1E-12 +CJ=1.157423E-3 MJ=0.4063933 CJSW=1.902456E-10 +MJSW=0.3550788 CJSWG=4.22E-10 LKETA=-2.936093E-3 +PUB=1E-21 PVTH0=1.4398E-3 PRDSW=0.5073407 PVSAT=-50 +PK2=2.190431E-3 WKETA=0.0442978 PU0=-0.9769623 +PUA= -4.34529E-11 PETA0= 1.002762E-4 PKETA =-6.740436E3)
.MODEL CMOSN NMOS (LEVEL=7 VERSION=3.1 TNOM=27 +W0=1E-7 UTE=-1.5 TOX=4E-9 XL=0 XJ=1E-7 NCH=2.3549E17 +VTH0=0.1862648 K1=0.5802748 K2=3.124029E-3 K3=1E-3 +K3B=3.3886871 A0=2 WL=0 NLX=1.766159E-7 DVT0W=0 +DVT1W=0 DVT2W=0 DVT0=1.2312416 DVT1=0.3849841 A2=1 +DVT2=0.0161351 U0=265.1889031 LL=0 WR=1 WINT=0 +VSAT=1.017932E5 B1=5E-6 A1=1.158074E-3 UA=-1.506402E-9 +UB=2.489393E-18 UC=5.621884E-11 XW=-1E-8 AGS=0.4543117 +B0=3.433489E-7 PRWG=0.5 KETA= -0.0127714 CIT=0 +RDSW=36.5582806 KT1=-0.11 PRWB=-0.2 LINT=1.702415E-8 +DWG=-4.211574E-9 DWB=1.107719E-8 CDSC=2.4E-4 +CDSCD=0 VOFF=-0.0948017 NFACTOR=2.1860065 CDSCB=0 +AT=3.3E4 ETA0=3.335516E-3 KT1L=0 DELTA=0.01 +ETAB=6.028975E-5 DSUB=0.0214781 PCLM=0.6602119 +PDIBLC1=0.1605325 PDIBLC2=3.287142E-3 PDIBLCB=-0.1 +MOBMOD=1 WLN=1 DROUT=0.7917811 PSCBE1=6.420235E9 +PSCBE2=4.122516E-9 PVAG=0.0347169 RSH=6.6 PRT=0 +KT2=0.022 WW=0 UA1= 4.31E-9 UB1=-7.61E-1 UC1=-5.6E-11 + WWN=1 WWL=0 LLN=1 LW=0 LWN=1 LWL=0 CF=0 +CAPMOD =2 PBSW= 0.8 PB=0.8 XPART=0.5 CGDO=8.06E-10 +CGSO=8.06E-10 CGBO=1E12 CJ=9.895609E-4 MJ=0.3736889 +CJSWG=3.3E-10 CJSW=2.393608E-10 MJSW=0.1537892 +PBSWG=0.8 MJSWG=0.1537892 PVTH0=-1.73163E-3 +PK2=1.600729E-3 PRDSW=-1.4173554 WKETA=1.601517E-3 +PU0=5.2024473 PUA=1.584315E-12 LKETA=-3.255127E-3 +PUB=7.446142E25 PVSAT=1.686297E3 PETA0=1.001594E-4 +PKETA= -2.039532E-3)

For SPICE simulations, the W/L ratios of the MOSFETs used for implementing the CFOA, were chosen as given in Table 2, whereas the aspect ratios of the MOSFETs used to realize the floating VCR circuit were as given in Table 3. Lastly, the model parameters for 0.18μm Technology were taken as given in Table 4.

The SPICE simulation results of the proposed circuit as a linear VCOs are shown in Figure 3 and Figure 4 which show the variation of oscillation frequency with control voltage also.

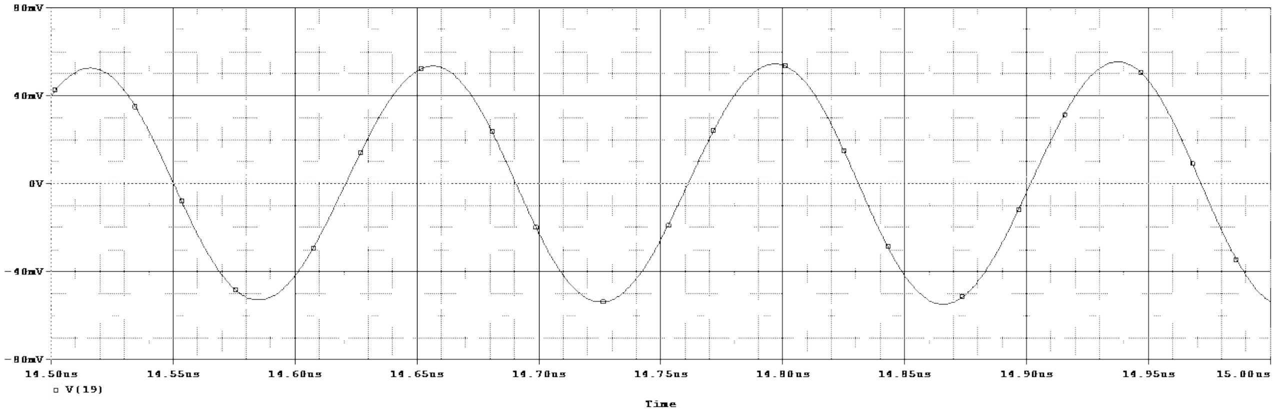

Figure 3. Frequency (Simulated)=7.133MHz,THD = 1.83 % with component values C_1= 20pF C_2=10pF C_3=30pF,V_n= 0.75V,V_p= -0.9V

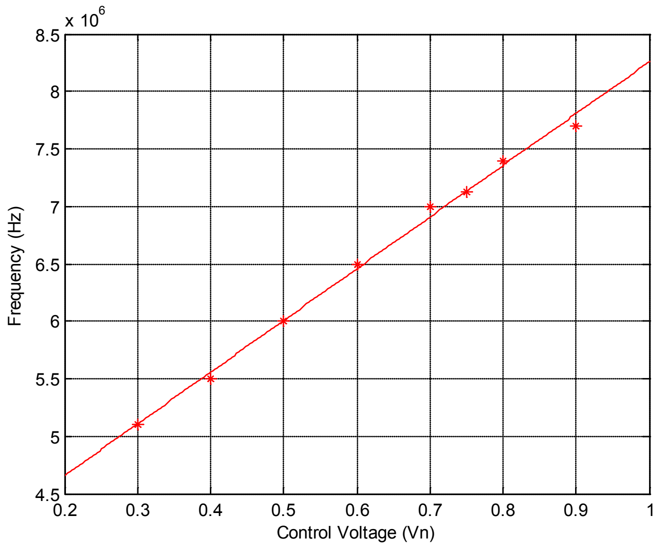

Figure 4. Variation of oscillation frequency with control voltage

From the SPICE simulations, the circuit was found to perform as predicted by the theory with excellent linearity with respect to the external control voltage. Simulations have shown it to be possible to vary the oscillation frequency from 5.1MHz to 8.4MHz by varying control voltage from 0.3V to 1.4V with % error in the realized frequency lying between 0.0067% to -0.009% only. The power consumed by the circuit was 19.4nW only.

5. Comparison with Previously Published Current Conveyors/CFOA-based VCOs

A comparison of the proposed new single-CFOA-based VCO with the previously published Current Conveyors (CC) or CFOA-based VCOs is now in order. It is found that the proposed circuit attains most of the desirable features using only a single CFOA, three grounded capacitors (as preferred for IC implementation [25,26,27,28]) along with four MOSFETs only, in contrast to the previously known CC/CFOA-based VCOs of [2,10,18,20,21,22,23], which suffer from the drawbacks of requiring two or more building blocks [2,9] along with other devices like either a FET and a few additional resistors [18] or eight to twelve MOSFETs [10] or two analog multipliers [20,21,22,23].

6. Concluding Remarks

A simple single-CFOA-based three-capacitor-two-resistor oscillator circuit was the main focus of this article which has a tuning law in which two resistors appearing as product in the expression for oscillation frequency appear as a resistor-ratio in the condition of oscillation. By replacing these two resistors by two identical CMOS VCRs derived by a common control voltage, oscillation frequency becomes a *linear* function of the control voltage, whereas the oscillation condition remains unaffected by this process. The workability of the completely CMOS-compatible version of the circuit obtained by using a CMOS CFOA and CMOS VCRs was verified by SPICE simulations from which the linearity of the variation in the oscillation frequency, with respect to the control voltage, was found to be as predicted by the theory. Lastly, it may be mentioned that the proposed circuit attains most of the desirable features using only a single CFOA, three grounded capacitors (as attractive for IC implementation [25,26,27,28]) and four MOSFETs only in contrast to the previously known CC/CFOA-based VCOs of [2,9,10,18,20,21,22,23].

References

[1] Y. Tsividis, M. Banu, J. Khoury, "Continuous-time MOSFET-C filters in VLSI" *IEEE Journal of Solid-State Circuits*, 21, 15-30, 1986.

[2] D. R. Bhaskar, R. Senani, "New current-conveyor-based single-resistance-controlled/voltage-controlled oscillator employing grounded capacitors" *Electronics Letters,* 29, 612-614,1993 .

[3] S. Celma, PA Martinez, A. Carlosena, "Current feedback amplifiers based sinusoidal oscillators" *IEEE Trans Circuits and Syst-I: Fundamental Theory and Applications*, 41, 906-908, 1994.

[4] R. Senani, V.K. Singh, "Novel single resistance controlled oscillator configuration using current feedback amplifiers" *IEEE Trans Circuits and Syst-I: Fundamental Theory and Applications*; 43, 698-700, 1996.

[5] R. Senani, V.K. Singh, "Comment: Synthesis of canonic single resistance controlled oscillators using single current feedback amplifier" *IEE Proc Circuits Device*; 143(1), 71-72, 1996.

[6] M.T. Abuelma′atti, S.M. Al-Shahrani, "A Novel low-component-count single-element-controlled sinusoidal oscillator using the CFOA pole", *Int J Electron,* 80(6),747-752,1996.

[7] M.T. Abuelma′atti, S.M. Al-Shahrani, "New CFOA-based grounded-capacitor single element controlled sinusoidal oscillator", *Active and Passive Electronic Components,* 20,119-124, 1997.

[8] R. Senani, "Realization of a class of analog signal processing/signal generation circuits: novel configurations using current feedback op-amps", *Frequenz,* 52, 196-206, 1998.

[9] D. R. Bhaskar, M. P. Tripathi, "Realization of novel linear sinusoidal VCOs", *Analog Integrated Circuits and Signal Processing*, 24, 263-267, 2000.

[10] S.A. Mahmoud, A.M. Soliman, "Novel MOS-C oscillators using the current feedback op-amp", *Int J Electron*, 87, 269-280, 2000.

[11] V.K. Singh, R.K. Sharma, A.K. Singh, D.R. Bhaskar, R. Senani, "Two new canonic single-CFOA oscillators with single resistor controls", *IEEE Trans. on Circuits and Systems-II, Express Briefs,* 52, 860-865, 2000.

[12] A.M. Soliman, "Current feedback operational amplifier based oscillators", *Analog Integrated Circuits and Signal Processing*, 23, 45-55, 2000.

[13] U. Cam, "A Novel single-resistance-controlled sinusoidal oscillator employing single operational trans-resistance amplifier", *Analog Integrated Circuits and Signal Processing*, 32, 183-186, 2002.

[14] A. Toker, O. Cicekoglu, H. Kuntman, "On the oscillator implementations using a single current feedback op-amp", *Computers and Electrical Engineering*, 28, 375-389, 2002.

[15] D. R. Bhaskar, R. Senani, "New CFOA-based single-element-controlled sinusoidal oscillators", *IEEE Transactions on Instrumentation and Measurement*, 55, 2014-2021, 2006.

[16] H.P. Chen, K.H. Wu, "Voltage-mode DDCC-based multifunction filters", *Journal of Circuits, Systems and Computers*, 16, 93-104, 2007.

[17] S.M. Al-Shahrani, "CMOS wideband auto-tuning phase shifter circuit", *Electronics Letters*, 43, 804-805, 2007.

[18] S.S. Gupta, D.R. Bhaskar, R. Senani, "New voltage controlled oscillators using CFOAs", *Int J Electron Commun (AEÜ)*, 63, 209- 217, 2009.

[19] R. Senani, D.R. Bhaskar, S.S.Gupta, V.K.Singh, "A configuration for realizing floating, linear, voltage-controlled resistance, inductance and FDNC Elements", *International Journal of Circuit Theory and Applications*, 37, 709-719, 2009.

[20] D.R. Bhaskar, R. Senani, A.K. Singh, S.S. Gupta, "Two simple analog multipliers based linear vco's using a single current feedback op-amp", *Circuits and Systems*, 1, 1-4, 2010.

[21] D.R. Bhaskar, Raj Senani, A.K. Singh, "Linear sinusoidal vco's: new configurations using current-feedback-op-amps", *Int. J Elec,* 97, 263-272, 2009.

[22] S.S. Gupta, D.R. Bhaskar, R. Senani, A.K. Singh, "Synthesis of Linear vco's: The state-variable approach" *Journal of Circuits, Systems and Computers*, 20, 587-606, 2011.

[23] S.S. Gupta, D.R. Bhaskar, R. Senani, "Synthesis of new single CFOA-based vco's incorporating the voltage summing property of analog multipliers", *ISRN Electronics*, 1-8, 2012.

[24] R. Senani, D.R. Bhaskar, A.K. Singh, V.K. Singh, "Current feedback operational amplifiers and their applications". *Springer Science + Business Media, New York* 2013, Chapter 5, 131-176.

[25] R. Senani, D.R. Bhaskar, V.K. Singh R.K. Sharma, "Sinusoidal oscillators and waveform generators using modern electronic circuit building blocks". *Springer International Publishing, Switzerland* 2016; Chapter 5: 213-264.

[26] R.W. Newcomb, "Active integrated circuit synthesis", *Prentice-Hall Electrical Engineering Series,* 1-292, 1968.

[27] M. Bhushan, R. Newcomb, "Grounding of capacitors in integrated circuits", *Electronics Letters,* 3, 148-149, 1967.

[28] S.S. Gupta, R. Senani, "Realization of current-mode SRCO's using all grounded passive elements", *Frequenz,* 57, 26-37, 2003.