LETTER

Voltage-variable inductor based linear voltage controlled quadrature oscillator implementation

Koushick Mathur¹, Palaniandavar Venkateswaran², and Rabindranath Nandi^{2a)}

Abstract A new voltage-variable inductor (VVI)-L realization scheme using composite Current Feedback Amplifier (CFA) and Multiplication Mode Current Conveyor (MMCC) active building block (ABB) is presented. Subsequently a LC-type voltage controlled quadrature oscillator (VCQO) with linear tuning law is derived by replacing the CFA by another MMCC. Experimental results based on PSPICE simulation and hardware circuitry for a linear tuning range of oscillation frequency (f_o) $\sim$ 9.3 MHz with satisfactory phase-noise figure on the wave generation, had been verified. Effects of the ABB nonidealities are shown to be insignificant.

Keywords: CFA, MMCC, voltage variable inductor, quadrature oscillator, linear VCO, analog multiplier

Classification: Integrated circuits

1. Introduction

A new lossless VVI(L) simulation scheme with a grounded capacitor using a composite CFA-MMCC block [1, 2] is presented, wherein no component matching criterion is needed. Next a linear VCQO is implemented by inserting another MMCC in place of the CFA. Recent literature indicates only a few designs of electronically tunable-L, in which device trans-conductance (g_m) or bias current (I_b) is the tuning parameter. This requires additional current processing circuitry that attracts issues of thermal voltage (V_T) and quiescent dissipation. Here oscillation frequency (f_o) of the QO is tunable by the MMCC control voltage (V) with a linear law. Effects of device nonidealities, viz., parasitic capacitors and roll-off poles of device port coefficients are negligible. A listing of recent electronically tuned-L designs are shown in Table I.

2. VVI design

Circuit implementation of the VVI is shown in Fig. 1(a), where $C_{z1,2}$ and $C_{y1,2}$ are device parasitic capacitances. The input admittance is

$$Y_i = sC_b + (1/s\dot{L}); \quad \dot{L} = C_o R_1 R_2 (1 + \mu)/kV \quad (1)$$

¹Department of Electronics & Communication Engineering, Burdwan University-UIT, WB-713104, India

²Department of Electronics & Telecommunication Engineering, Jadavpur University, Kolkata-700032, India

a) robnon@ieee.org

DOI: 10.1587/elex.17.20190738

Received December 15, 2019

Accepted January 29, 2020

Publicized February 13, 2020

Copyedited March 10, 2020

Table I. Summary of recent VVI schemes

Ref.	ABB	Tunability by	Select frequency f_o (Hz)
[3]	CFA-JFET	r_{ds}	1 M
[4]	MVDVTA	g_m -V	2.5 M
[5]	CCCCTA-Opamp	g_m	100 K
[6]	LT-1228 (OTA)	g_m -(I_b)	200 K
[7]	VD-DIBA	g_m -(I_b)	1 M
[8]	OTA	I_b	10 K
[9]	DO-CCCII	($I_b/2V_T$)	100 K
Proposed:	CFA-MMCC	V_{dc}	6 M

where $k \approx 1/\text{volt.d.c}$ [10, 11] is the multiplication constant of the MMCC and $\mu = C_a/C_o \ll 1$; $C_a = C_{z1} + C_{y2}$ and $C_b = C_{y1} + C_{z2}$. Values of parasitic capacitors are quite low ($3 < C_{y,z}$ (pF) < 5) as per databook [12]; these may induce some self-oscillatory feature at very high frequencies ($f > 100$ MHz) with typical L-values ($\sim 30 \mu\text{H}$) if $C_o \sim 30$ pF with $R \sim 1 \text{ K}\Omega$ values. The characteristics of this VVI had been verified by a typical RLC-bandpass (BP) filter with resonant frequency in a range of $6 < f_r$ (MHz) < 9 for stable operation.

Effects of the device rolloff poles had been estimated by writing $I_z = \alpha_{1,2} I_x$, $V_w = \delta_{1,2} V_z$ and $V_x = \beta_1 V_y$, $V_x = \beta_2 k V V_y$; subscripts 1 and 2 are for the CFA (AD-844) and MMCC respectively. The modified input impedance in Fig. 1(a) is

$$\dot{Z}_i = Z_i/\alpha_1 \beta_1 \alpha_2 \delta_2 \quad (2)$$

where $\alpha_{1,2} = (1 - \varepsilon_{i,1,2})/(s\tau_{i,1,2} + 1)$, $\beta_1 = (1 - \varepsilon_{v1})/(s\tau_{v1} + 1)$ and $\delta_2 = (1 - \varepsilon_{o1})/(s\tau_{o1} + 1)$. The d.c. gain-errors are quite negligible ($\varepsilon \ll 1$) [13]; rolloff poles appear at very high frequency ($\gg 100$ MHz) ranges and they lie at close proximity [14]. Hence, we may write $\tau_{i,v,z} \approx \tau \equiv 1/\omega_p$ which yields

$$\alpha_1 \beta_1 \alpha_2 \delta_2 = 1/\{(s\tau)^4 + (4s\tau)^3 + (6s\tau)^2 + 4s\tau + 1\} \quad (3)$$

Neglecting higher-order terms and writing $s\tau = j\omega\tau \equiv j\omega/\omega_p \approx ju$ for frequency-domain; we get a modified L-value with $u \ll 1$, as

$$\dot{L}/L \approx \{1/\sqrt{(1 + 16u^2)}\}_L - \arctan(4u); \quad u \ll 1 \quad (4)$$

Therefore effects of device rolloff poles are quite negligible. An application of the proposed VVI in a selective-BP filter with a shunt capacitor (C_s) and series resistor (r) as in Fig. 1(a) is designed with transfer function $V_o/V_i(s) \equiv F(s)$ is

$$F(s) = (sL/r) / \{s^2LC_s(1+m) + (sL/r) + 1\} \quad (5)$$

where $\omega_r = 1/\sqrt{\{LC_s(1+m)\}}$, $L = C_oR_1R_2/kV$, $m = C_b/C_s < 1$, and $Q = \omega_r L/r$. Thus resonant frequency ω_r and Q are independently adjustable without any component matching constraint.

Fig. 1. Circuit implementation of (a) VVI based BPF and (b) LVCQO

3. LVCQO implementation

Albeit quite a number of electronically tunable quadrature oscillators had been reported in recent past [5, 15, 16, 17, 18, 19, 20, 21, 22, 23, 24, 25, 26, 27, 28, 29], only a few have a linear tuning law as listed in Table II. These are mostly tuned by bias current (I_b) of some trans-conductance device, which attracts issues of thermal voltage (V_T) and quiescent dissipation. The proposed shunt-LC oscillator implementation is realized by replacing the CFA in Fig. 1(a) by a MMCC element after disconnecting the series resistor (r) of the filter configuration; this yields a LVCQO in Fig. 1(b) given by the loop characteristics equation as

$$s^2C_oC_s(1+\lambda) + (kV)^2R_1R_2 = 0; \quad \lambda = (C_a + C_b)/C_s \ll 1 \quad (6)$$

The oscillation frequency is

$$\omega_o = kV/\sqrt{R_1R_2C_oC_s} \quad (7)$$

Hence ω_o is multiplier-V tunable with a linear law.

4. Experimental results

The design implementations had been tested by using the AD-844 CFA device; the MMCC is fabricated by readily available CFA and AD-835/734 analog multiplier ($k = 1$) [30, 31]; AD-734 is a recent replacement of AD-835. Measured responses of both VVI as a BP-filter, the tuning graph, wave response and phase-noise of LVCQO are shown in Fig. 2. V-tuning law had been derived for the oscillator by using $R_1 = R_2 = 2.2 \text{ K}\Omega$ and $C_o = C_s = 40 \text{ pF}$, given by $f_o \text{ (MHz)} = 1.8 \text{ V}$. The phase-noise of $f_o = 7.4 \text{ MHz}$ of generated signal is verified as (-107 dbc/Hz) @ offset frequency of 7.5 KHz ; which is comparatively better to other similar previous work [29]. The linearity-error had been evaluated from the response-graph as:

Slope of the practical = $(8.84 - 1.81) \text{ MHz/(5 - 1) V.d.c.}$

$$= 1.76 \text{ MHz/V} \equiv \epsilon_2$$

Theoretical slope as derived as: $\epsilon_1 = 1.8 \text{ MHz/V.d.c.}$

Thus the nonlinearity error is $\epsilon_o = (\epsilon_1 - \epsilon_2)/\epsilon_1 \equiv 2.2\%$.

Table II. Summary of recent electronically tunable QOs

Ref.	ABB	f_o (KHz)	Tuned by	Linear law
5	MDVTA	2500	$\sqrt{g_m}$	x
15	OTA	64	I_b	Y
16	DVCCTA	348	$\sqrt{I_b}$	x
17	CDTA	1000	$\sqrt{g_m}$	x
18	DVCCCTA	1100	$\sqrt{g_m}$	x
19	ZC-CG-CDBA	2750	Current-gain	Y
20	CDTA	183	$\sqrt{I_b}$	x
21	CCCDDBA	420	$\sqrt{I_b}$	x
22	VDIBA	8500	$\sqrt{I_b}$	x
23	DVCCTA	3200	$\sqrt{g_m}$	x
24	CCTA	1560	$\sqrt{I_b/V_T}$	x
25	CCCTA	1100	$\sqrt{g_m}$	x
26	OTA	1590	$\sqrt{g_m}$	x
27	CCCCTA	1000	I_b	Y
28	MMCC	3300	V	Y
29	VDTA	3.17	I_b	x
Proposed	MMCC	9300	V	Y

Fig. 2. Experimental results VVI and LVCQO

- (a) VVI based BPF ($f_o = 6$ MHz & $Q = 5.9$)
 (b) Linear tuning Law
 (c) Quadrature waveform at 7.4 MHz
 (d) Spectrum of 7.4 MHz wave

5. Conclusion

A new electronically tunable grounded lossless inductor realization scheme using composite CFA-MMCC building block is presented along with its application to a selective ($Q \sim 6$) BP-filter. A linear VCO with quadrature signal generation attribute is subsequently implemented by replacing the CFA with another MMCC; the f_o -tunability

(~ 9.3 MHz) is measured by both PSPICE and hardware test-set up after configuring the MMCC block with readily available CFA-analog multiplier devices. Here no component matching requirement is needed and both capacitors are grounded such that the parasitic capacitors may be absorbed in them.

References

- [1] *Analog Devices: Linear Products Databook* (M.A., USA, 1990).
- [2] Y. S. Hwang, *et al.*: "New building block: Multiplication mode current conveyor," *IET Circuits Dev. Syst.* **3** (2009) 41 (DOI: [10.1049/iet-cds:20080156](https://doi.org/10.1049/iet-cds:20080156)).
- [3] R. Senani, *et al.*: "A configuration for realizing floating, linear, voltage-controlled resistance, inductance and FDNC elements," *Int. J. Circuit Theory Appl.* **37** (2009) 709 (DOI: [10.1002/cta.510](https://doi.org/10.1002/cta.510)).
- [4] S. Lawanwisut and M. Siripruchyanun: "An electronically controllable active-only current-mode floating inductance simulator," *Proc. 35th Int. Conference on Telecommunications and Signal Processing* (2017) 389 (DOI: [10.1109/TSP.2012.6256321](https://doi.org/10.1109/TSP.2012.6256321)).
- [5] H. Alpaslan: "A modified VDVTA and its applications to floating simulators and quadrature oscillator," *Microelectronics J.* **51** (2016) 1 (DOI: [10.1016/j.mejo.2016.02.001](https://doi.org/10.1016/j.mejo.2016.02.001)).
- [6] S. Siripongdee and W. Jaikla: "Electronically controllable grounded inductance simulators using single commercially available IC: LT1228," *AEU - Int. J. Electron. Commun.* **76** (2017) 1 (DOI: [10.1016/j.aue.2017.03.018](https://doi.org/10.1016/j.aue.2017.03.018)).
- [7] D. Prasad, *et al.*: "Realization of new electronically controllable grounded & floating simulated inductance circuits using VD-DIBAs," *Active Passive Electron. Components* **2011** (2011) 101432 (DOI: [10.1155/2011/101432](https://doi.org/10.1155/2011/101432)).
- [8] U. E. Ayten, *et al.*: "Novel floating FDNR, inductor and capacitor simulator using CBTA," *Proc. 34th Int. Conf. on TSP* (2011) (DOI: [10.1109/TSP.2011.6043719](https://doi.org/10.1109/TSP.2011.6043719)).
- [9] M. Sagbas, *et al.*: "Electronically tunable floating inductance simulator," *AEU - Int. J. Electron. Commun.* **63** (2009) 423 (DOI: [10.1016/j.aue.2008.02.016](https://doi.org/10.1016/j.aue.2008.02.016)).
- [10] Analog Device Datasheet: AD835 and AD534: 250 MHz, 4-quadrant voltage multiplier. file#D00883-0-12/14(E) (2017).
- [11] Intersil Datasheet: file#2477.5, September 1998 and file#2863 (1999).
- [12] Macromodel of AD-844AN in PSPICE Library (Microsym Corp., Irvine, USA, 1992).
- [13] A. A. Tammam, *et al.*: "Critical review of the circuit architecture of CFOA," *Int. J. Electron.* **101** (2014) 441 (DOI: [10.1080/00207217.2013.780309](https://doi.org/10.1080/00207217.2013.780309)).
- [14] S. J. G. Gift and B. Maundy: "Improving the bandwidth-gain independence and accuracy of the current feedback amplifier," *IEEE Trans. Circuits Syst., II, Exp. Briefs* **52** (2005) 136 (DOI: [10.1109/TCSII.2004.842043](https://doi.org/10.1109/TCSII.2004.842043)).
- [15] K. Kumwachara and W. Surakamponorn: "An integrable temperature-insensitive gm-RC quadrature oscillator," *Int. J. Electron.* **90** (2003) 599 (DOI: [10.1080/0014184032000159363](https://doi.org/10.1080/0014184032000159363)).
- [16] A. Lahiri, *et al.*: "Voltage mode quadrature sinusoidal oscillator with current tunable properties," *Analog. Integr. Circ. Sig. Process.* **65** (2010) 321 (DOI: [10.1007/s10470-010-9488-2](https://doi.org/10.1007/s10470-010-9488-2)).
- [17] J. W. Horng, *et al.*: "Electronically tunable third-order quadrature oscillator using DTAs," *Radioengineering* **19** (2010) 326.
- [18] W. Jaikla, *et al.*: "Resistorless dual-mode quadrature sinusoidal oscillator using a single active building block," *Microelectronics J.* **42** (2011) 135 (DOI: [10.1016/j.mejo.2010.08.017](https://doi.org/10.1016/j.mejo.2010.08.017)).
- [19] D. Biolek, *et al.*: "Realization of electronically tunable voltage-mode/current-mode quadrature sinusoidal oscillator using ZC-CG-CDBA," *Microelectronics J.* **42** (2011) 1116 (DOI: [10.1016/j.mejo.2011.07.004](https://doi.org/10.1016/j.mejo.2011.07.004)).
- [20] J. Jin and C. Wang: "Single CDTA-based current-mode quadrature oscillator," *AEU - Int. J. Electron. Commun.* **66** (2012) 933 (DOI: [10.1016/j.aue.2012.03.018](https://doi.org/10.1016/j.aue.2012.03.018)).
- [21] F. Khateb, *et al.*: "Electronically tunable voltage mode quadrature oscillator based on high performance CCCDBA," *Analog. Integr. Circ. Sig. Process.* **74** (2013) 499 (DOI: [10.1007/s10470-012-](https://doi.org/10.1007/s10470-012-)

- 9997-2).
- [22] N. Herencsar, *et al.*: “New resistorless and electronically tunable realization of dual-output allpass filter using VDIBA,” *Analog. Integr. Circ. Sig. Process.* **74** (2013) 141 (DOI: [10.1007/s10470-012-9936-2](https://doi.org/10.1007/s10470-012-9936-2)).
 - [23] H.-P. Chen, *et al.*: “Tunable current-mode and voltage-mode quadrature oscillator using a DVCCTA,” *IEICE Electron. Express* **11** (2014) 20140478 (DOI: [10.1587/elex.11.20140478](https://doi.org/10.1587/elex.11.20140478)).
 - [24] A. Jantakun: “A simple grounded FDNR and capacitance simulator based on CCTA,” *AEU - Int. J. Electron. Commun.* **69** (2015) 950 (DOI: [10.1016/j.aeue.2015.03.002](https://doi.org/10.1016/j.aeue.2015.03.002)).
 - [25] W. Sa-Ngiamvibool and A. Jantakun: “Quadrature oscillators using CCCCTAs and grounded capacitors with amplitude controllability,” *Int. J. Electron.* **101** (2014) 1737 (DOI: [10.1080/00207217.2014.896038](https://doi.org/10.1080/00207217.2014.896038)).
 - [26] N. Pandey and R. Pandey: “Approach for third-order quadrature oscillator realization,” *IET Circuits Dev. Syst.* **9** (2015) 161 (DOI: [10.1049/iet-cds.2014.0170](https://doi.org/10.1049/iet-cds.2014.0170)).
 - [27] Y. A. Li: “Derivation for current mode Wien oscillators using CCCCTAs,” *Analog. Integr. Circ. Sig. Process.* **84** (2015) 479 (DOI: [10.1007/s10470-015-0566-3](https://doi.org/10.1007/s10470-015-0566-3)).
 - [28] R. Nandi, *et al.*: “Electronically tunable allpass filter: Linear VCO design,” *IEICE Electron. Express* **13** (2016) 20160059 (DOI: [10.1587/elex.13.20160059](https://doi.org/10.1587/elex.13.20160059)).
 - [29] H.-P. Chen, *et al.*: “A new resistorless and electronic tunable third-order quadrature oscillator with current and voltage outputs,” *IETE Tech. Rev.* **35** (2017) 426 (DOI: [10.1080/02564602.2017.1324329](https://doi.org/10.1080/02564602.2017.1324329)).
 - [30] R. Nandi, *et al.*: “MMCC based electronically tunable all-pass filters using grounded synthetic inductor,” *Circ. Syst.* **5** (2014) 89 (DOI: [10.4236/cs.2014.54011](https://doi.org/10.4236/cs.2014.54011)).
 - [31] AD 734: 10 MHz four quadrant multiplier/divider. Analog Devices Datasheet; Rev. E, p. 16 (2011).