Log-domain Current-mode Third-order Sinusoidal Oscillator

Pipat Prommee[1] *and Krit Angkeaw*[2]

[1]Department of Telecommunications Engineering, Faculty of Engineering
King Mongkut's Institute of Technology Ladkrabang, Bangkok 10520, Thailand
[2]Instrumentation and Electronics Engineering Department, Faculty of Engineering
King Mongkut's University of Technology North Bangkok, Bangkok 10800, Thailand.
Email: pipat@telecom.kmitl.ac.th

***Abstract*— This paper describes the design of the third-order sinusoidal oscillator based on log-domain filtering concept. The circuit consists of two inverting lossy integrators and one inverting lossless integrator. The circuit employs only NPN-transistors. This proposed circuit can be instantaneously controlled over a very wide frequency range by adjusting bias currents for oscillation frequency which are indicated proposed circuit suitability in high-frequency applications. The oscillation condition and frequency of oscillation can be tuned by bias current. Sinusoidal frequency output can be obtained up to 100MHz with low THD and low number of transistors. Characteristics of this circuit are simulated using PSpice and they are found in agreement with the theory.**

Keywords: third-order sinusoidal oscillator, high-frequency, log-domain

I. INTRODUCTION

At present, there is a growing interest in synthesizing current-mode circuits because of their advantages such as high speed, greater linearity and low power consumption. The log-domain technique is a promising approach of designing high performance analogue current-mode cells. In 1979 R.W. Adams introduced a novel class of continuous-time filters call log-domain filters that externally are linear systems, yet internally are nonlinear [1]. This approaches to building linear filters from nonlinear components. In 1993 and 1996, Frey [2-3], [5] substantially extended Adam state-variable approach and came up with a quite general and very useful synthesis method for general higher order log-domain filters. This method had very impressive results in terms of the possible high frequency of operation, low supply voltage and electronically tunable [4]–[8].

Multiphase Sinusoidal Oscillator (MSO) has wide applications especially in communications which are used for single sideband generators and vector generators in measurement. For this reason a number of MSO have been realized by using different active devices and different techniques. Some quadrature oscillators are reported based on current feedback amplifier (CFA) [9-10] CDTA [11-12], OTA [13], FTFN [14], FDCCII [15] and DVCC [16] with large number of passive components in addition to these circuits without the electronic tuning feature. Recently, low-order oscillator function is definitely less accurate than high-order counterpart. OTA [17], CCCII [18] with grounded capacitors are used for third-order oscillator realization. Most of these circuits can be tuned within a narrow frequency range, not suitable for high-frequency operations and used many transistors. Therefore, the structure of these circuits could not be compacted.

The new proposed third-order sinusoidal oscillator is based on the use of current mode building blocks in the form of two inverting lossy integrators and one inverting lossless integrator. Fast response, wide range electronic tunability of the oscillation frequency, high-frequency operation and low-power supply are obtained consequently by using the log-domain concept.

II. THEORY AND PRINCIPLE

A. Oscillator principle

The structure of third-order oscillator yields the better performance than second-order oscillator especially in the THD. According to the operating principle of the oscillator based on Barkhausen's criteria, this paper is realized by using third-order polynomials which formed by Laplace equation in Eq. (1)

$$1-LG=\frac{N(s)}{D(s)}=0=\frac{a_0s^3+a_1s^2+a_2s+a_3}{b_0s^3+b_1s^2+b_2s+b_3} \tag{1}$$

Whereas $N(s)$, $D(s)$ are, respectively, represented the numerator and denominator polynomials and LG denotes loop gain of the system. Due to third-order polynomial as Eq. (1), the numerator $N(s)=0$ is a significant. Substituting $s=j\omega$, the numerator in Eq. (1) is rewritten as

$$0=N(j\omega)=-j\omega^3a_0-\omega^2a_1+j\omega a_2+a_3 \tag{2}$$

From Eq. (2), the condition of oscillation is given by

$$a_1a_2-a_0a_3=0 \tag{3}$$

and oscillation frequency yields

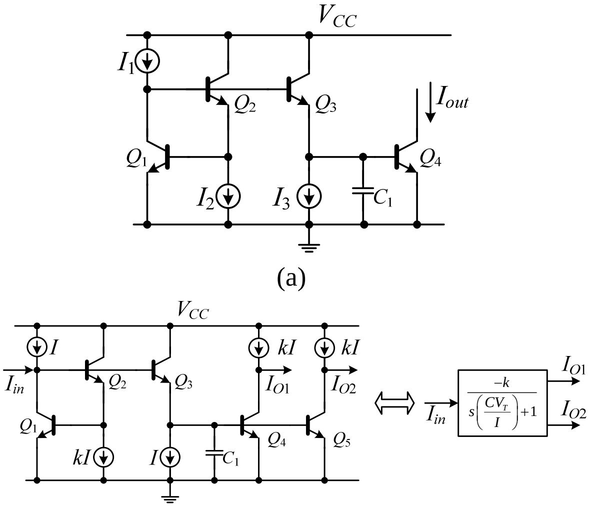
$$\omega^2=\frac{a_2}{a_1}=\frac{a_3}{a_1} \tag{4}$$

Based on this principle, third-order oscillator can be realized by using generalized third-order filters.

B. Log-domain lossy integrator

Fig 1 (a) show a log-domain filtering based on translinear type-B (Balance) cell which is called log-domain lossy integrator. Assuming that, each transistor has an ideal exponential characteristic. The base-emitter voltage can be express as Eq.(5) by using Kirchhoff's current law (KCL).

$$V_{be1} + V_{be2} - V_{be3} - V_{be4} = 0 \tag{5}$$



(a)

(b)

Fig.1 Log-domain lossy integrator (a) General form (b) Practical form

The collector current of transistor gives

$$I_C = I_S \exp\left(\frac{V_{be}}{V_T}\right) \tag{6}$$

Applying the translinear principle (TLP) [21] to Q_1-Q_4 gives:

$$I_{C1} I_{C2} = I_{C3} I_{C4} \tag{7}$$

Suppose that if $I_{C1} = I_1 = I_{in}$ and $I_{C4} = I_4 = I_{out}$ then Eq. (7) becomes

$$I_{in} I_2 = I_{C3} I_{out} \tag{8}$$

Collector current of Q_3 can be expressed as

$$I_{c3} = I_3 + C_1 \dot{V}_{C_1} \tag{9}$$

The derivative of the voltage across the capacitor

$$\dot{V}_{C_1} = \frac{dV_{C_1}}{dt} = \frac{V_T}{I_{out}} \frac{dI_{out}}{dt} = \frac{\dot{I}_{out}}{I_{out}} V_T \tag{10}$$

The derivative of the output current based on Eq. (6) yields

$$\dot{I}_{out} = \frac{dI_{out}}{dt} = \frac{I_S}{V_T} \exp\left(\frac{V_{C_1}}{V_T}\right) \frac{dV_{C_1}}{dt} = \frac{I_{out}}{V_T} \dot{V}_{C_1} \tag{11}$$

Substituting Eq. (9), (10) and (11) into Eq. (8) , we get

$$I_{in} I_2 = \left(I_3 + \frac{C_1 \dot{I}_{out} V_T}{I_{out}} \right) I_{out} \tag{12}$$

Suppose we define the bias currents $I_2 = kI_3 = kI$, then Eq. (12) becomes

$$kI_{in} = I_{out} + \frac{C_1 \dot{I}_{out} V_T}{I} \tag{13}$$

By taking the Laplace transform of both sides of Eq.(13) and rearranging, the transfer function of the circuit of Fig. 1(a)

$$H(s) = \frac{I_{out}(s)}{I_{in}(s)} = \frac{k}{s\left(C_1 V_T / I\right) + 1} \tag{14}$$

In practical case, the current $I_{C1} = I + I_{in}$, $I_{C2} = kI$. The constant bias current kI is inserted for cancel DC-term at the output as shown in Fig.1(b). The current output of the circuit can be expressed as

$$H(s) = \frac{I_{out}(s)}{I_{in}(s)} = \frac{-k}{s\left(C_1 V_T / I\right) + 1} \tag{15}$$

It is clear that the inverting lossy integrator circuits can be realized from this structure.

C. Log-domain lossless integrator

Lossless and lossy integrators perform as dependence building blocks with the same natural frequency, but lossy integrator performs as a first order low-pass filter. Lossy and lossless integrator can be transformed to each other. However, lossless integrator is transformed by using lossy integrator as shown in the literatures [19], [20]. This paper uses the transformation of lossless integrator realized by lossy integrator. The non-inverting lossless integrators in Fig. 2 can be realized by positive feedback output.

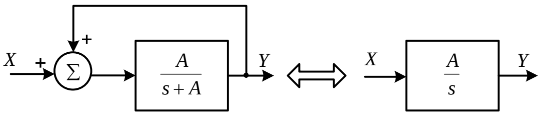


Fig. 2 Lossless integrator realized from lossy integrator

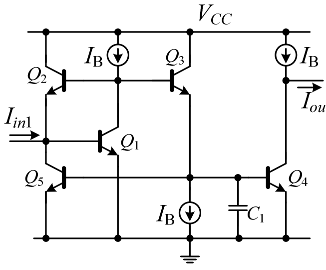


Fig.3 Non-inverting log-domain lossless integrator

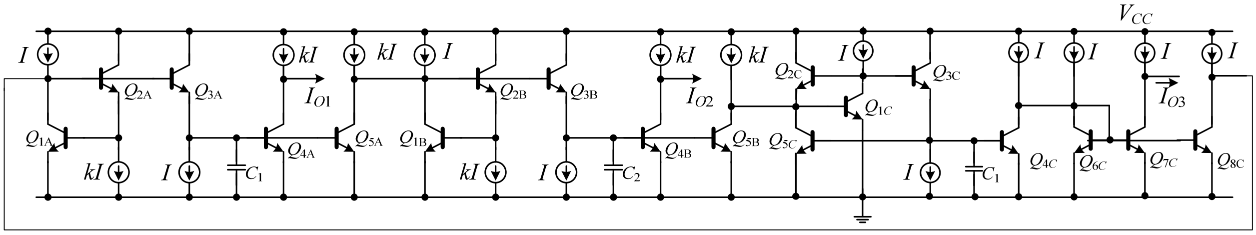


Fig. 5 Proposed log-domain current-mode third-order sinusoidal oscillator

Lossless integrator can be realized by loopback the output I_{out} into the positive input by using transistor Q_5 as shown in Fig.3. The completed non-inverting lossless integrator can easily be obtained. The inverting lossless integrator is also obtained by adding a simple current mirror which performs as inverting current buffer. The transfer function of lossless integrator is described as

$$\frac{I_{out}(s)}{I_{in1}(s)} = \frac{I_B}{sC_1V_T} \qquad (16)$$

III. LOG-DOMAIN THIRD ORDER SINUSOIDAL OSCILLATOR

The generalized structure of log-domain third order sinusoidal oscillator is realized by cascading two lossy integrators and a lossless integrator. The current output is loop-back to its input as shown in Fig.4. The function loop gain can be expressed as Eq.(17).

$$LG = \frac{-k_1k_2I^3 / C^3V_T^3}{s^3 + \frac{2I}{CV_T}s^2 + \frac{I^2}{C^2V_T^2}s} \qquad (17)$$

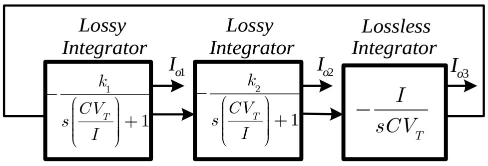


Fig.4 Block diagram of third-order oscillator

The characteristic equation can be expressed as

$$0 = -j\omega^3 - 2\frac{I\omega^2}{CV_T} + \left(\frac{I^2}{C^2V_T^2}\right)j\omega + \frac{k_1k_2I^3}{C^3V_T^3} \qquad (18)$$

The oscillation condition is given by

$$k_1k_2 = 2 \qquad (19)$$

The oscillation frequency can be obtained as

$$\omega = \frac{I}{CV_T} \qquad (20)$$

From Equations (1)-(4), it is clear that the oscillation condition and oscillation frequency can be written as Eq (19) and (20), respectively. The proposed circuits can be realized by using block diagram in Fig.4. The identical stage gain of both lossy integrators is defined ($k_1 = k_2 = k$). From Eq.(19), stage gain (k) of each lossy integrator is defined $k = \sqrt{2}$. The output of lossless integrator is fed back into the first lossy integrator.

IV. SIMULATION RESULTS

The proposed log-domain third-order sinusoidal oscillator circuit is verified through PSpice simulation using the circuit in Fig.5 with BJT transistors technology from Intersil as listed in Table 1. The power supplies is selected as V_{CC}=2V.

Table 1 Parameter of HFA3046 model provided by intersil used for SPICE simulation

```
.model NUHFARRY NPN
+ (IS=1.840E-16 XTI=3.000E+00 EG=1.110E+00 VAF=7.200E+01
+ VAR=4.500E+00 BF=1.036E+02 ISE=1.686E-19 NE=1.400E+00
+ IKF=5.400E-02 XTB=0.000E+00 BR=1.000E+01 ISC=1.605E-14
+ NC=1.800E+00 IKR=5.400E-02 RC=1.140E+01 CJC=3.980E-13
+ MJC=2.400E-01 VJC=9.700E-01 FC=5.000E-01 CJE=2.400E-13
+ MJE=5.100E-01 VJE=8.690E-01 TR=4.000E-09 TF=10.51E-12
+ ITF=3.500E-02 XTF=2.300E+00 VTF=3.500E+00 PTF=0.000E+00
+ XCJC=9.000E-01 CJS=1.150E-13 VJS=7.500E-01 MJS=0.000E+00
+ RE=1.848E+00 RB=5.007E+01 RBM=1.974E+00 KF=0.000E+00
+ AF=1.000E+00)
```

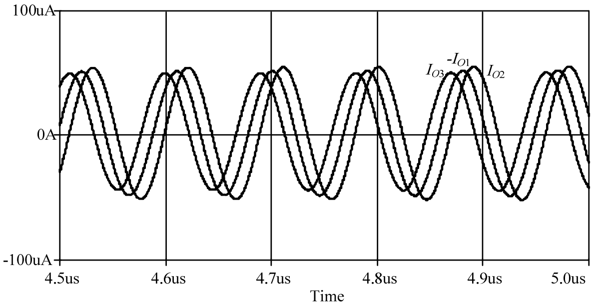


Fig. 6 Simulated results of three-phase current mode oscillator based on Fig.5 with I = 100 μA and C=50pF

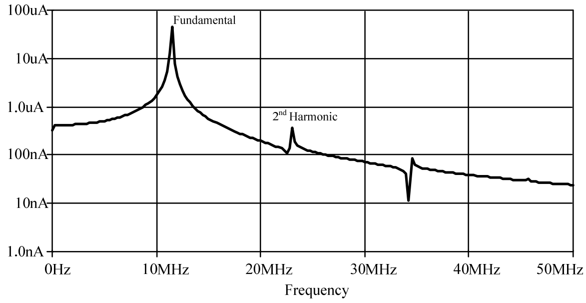


Fig. 7 Frequency Spectrum of signal Fig. 6 at 11.5 MHz

Three phase current outputs are illustrated in Fig.6 with k=1.5128, I=100 μA and C=50pF. These sinusoidal signals have around 45 degree phase difference. Proposed sinusoidal output signal of Fig.5 based on bias currents I=100 μA which is also contributed to prove of the THD characteristic. The 2nd and 3rd harmonic frequency components are respectively, around 364.74nA and 83.462nA while fundamental frequency at 11.5 MHz is 46.771μA. Hence, calculated THD is around 0.79% can be observed. The I_{O1}, I_{O2} and I_{O3} have small different amplitude because the different biasing and mismatch of summing current gain stages. However, the different amplitude of outputs is trivial which can easily be adjusted by either amplifier or attenuator.

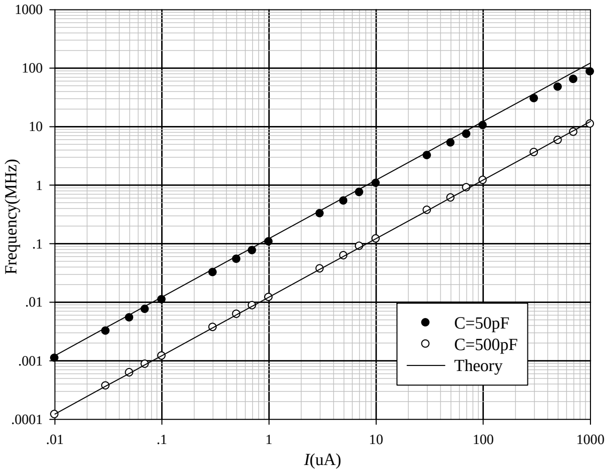


Fig.8 Tunable frequency of oscillation by using various bias current (I) and capacitors (C)

The tunable frequency of oscillation of third-order oscillator can be accommodated by varying current bias (I) from 0.01μA to 1000μA with different capacitor values. A comparison of the simulation and theoretical results are shown in Fig.8. A wide-range of frequency of oscillation from 1kHz to 100MHz can be obtained based on C_1=C_2=50pF and 100Hz to 10MHz can be obtained based on C_1=C_2=500pF. The theory and simulation results are in agreement with the theoretical.

V. CONCLUSION

This paper proposes a novel method for constructing a log-domain current-mode third-order sinusoidal oscillator. This circuit is realized by cascading two lossy and one lossless log-domain integrators with 18 transistors and 3 grounded capacitors. This proposed circuit has several advantages. For instance, low-voltage and oscillation frequency can be wide range tuned electronically more than five decade. Beside, oscillation frequency and oscillation conditions can simply be controlled by adjusting the bias current. THD value is obtained about 0.79%. Owing to the log-domain concept based on NPN transistors, the circuit is appropriated for integrated circuit and high frequency circuit.

REFERENCES

[1] R. W. Adams, "Filtering in the log domain," in *63rd AES Conf.*, New york, N Y, preprint 1470, May 1979.

[2] D. R. Frey, "Log-domain filtering: An approach to current-mode filtering," *Proc. IEE, part-G*, vol. 140, no. 6, pp. 406–416, 1993.

[3] D. R. Frey, "Exponential state-space filters: a generic current mode design strategy," *IEEE Trans Circuits Systems-I*, vol.43, pp.34–42, 1996.

[4] D. R. Frey, "A 3.3 V electronically tuneable active filter useable to beyond1 GHz," in *Proc. IEEE Int. Symp. Circuits Syst. (ISCAS'94)*, London,U.K., vol.5, pp. 493–496, 1994.

[5] D. R. Frey, "Log domain filtering for RF applications," *IEEE J.Solid-State Circuits*, vol.31, pp.1468–1475, Oct. 1996.

[6] D. R. Frey, "An adaptive analog notch filter using log-filtering," in *Proc. IEEE Int. Symp. Circuits Syst. (ISCAS'96)*, Atlanta, GA, vol.1, pp.297– 300, 1996.

[7] F. Yang, C. Enz, and G. Ruymbeke, "Design of low-power and low voltage log-domain filters," in *Proc. IEEE Int. Symp. Circuits Syst.(ISCAS'96)*, Atlanta, GA, vol.1, pp.117–120, 1996.

[8] E. M. Drakakis, A. J. Payne, and C. Toumazou, "Log-Domain Filtering and the Bernoulli Cell," *IEEE Trans. Circuits Syst. I*, vol.46, no.5, pp. 559–571, May.1999

[9] R. Nandi, S. K. Sanyal, and T. K. Bandyopadhyay, "Single CFA-Based Integrator, Differentiator, Filter, and Sinusoid Oscillator," *IEEE Trans. Instrum. Meas.*, Vol.58, No 8, Aug. 2009.

[10] R. Nandi, T. K. Bandyopadhyay, S. K. Sanyal and S. Das, "Selective Filters and Sinusoidal Oscillators Using CFA Transimpedance Pole," *Circuits System and Signal Processing*, Vol.28, pp.349–359, 2009.

[11] A.U. Keskin and D. Biolek, "Current-mode quadrature oscillator using current differencing transconductance amplifier (CDTA)," *IEE Proceeding of Circuits Devices and Systems*, Vol. 153, pp. 214-218, 2006.

[12] A. Lahiri, "Novel voltage-current-mode quadrature oscillator using current differencing transconductance amplifier," *Analog Integrated Circuits and Signal Processing*, Vol.6, pp.199–203, 2009.

[13] M.T. Ahmed, I.A. Khan, and N. Minhaj, "On transconductance-C quadrature oscillators," *International Journal of Electronics*, Vol. 83, pp. 201-207, 1997.

[14] S. I. Liu and Y. H. Liao, "Current-mode quadrature sinusoidal oscillator using single FTFN," *International Journal of Electronics*, Vol. 81, pp. 171-175, 1996.

[15] J.W. Horng, C.L. Hou, C.M. Chang, H.P. Chou, and Y.H. Wen, "Quadrature oscillator with grounded capacitors and resistors using FDCCIIs," *ETRI Journal*, Vol. 28, pp. 486-494, 2006.

[16] J.W. Horng, "Current-mode quadrature oscillator with grounded capacitors and resistors using two DVCCs," *IEICE Transaction on Fundamentals of Electronics, Communications and Computer Sciences*, Vol. E86-A, pp. 2152-2154, 2003.

[17] P. Prommee, K. Dejhan, "An integrable electronic-controlled quadrature sinusoidal oscillator using CMOS operational transconductance amplifier,". *International Journal of Electronics*, vol.89, no.5, pp.365-379, 2002.

[18] S. Maheshwari, and I.A Khan, "Current controlled third-order quadrature oscillator," *IEE Proceeding on Circuits Devices* Systems, vol.152, pp. 605-607, 2005.

[19] Kerwin W. J., Huelsman L. P., and Newcomb R. W., "State-variable synthesis for insensitive integrated circuit transfer function" *IEEE Trans. Solid-state Circuits*, 1967, SC-2, pp. 87-92.

[20] E. Sanchez-sinencio, R.L. Geiger and H. Nevarez-Lozano, "Generation of Continous-Time Two Integrator Loop OTA filter structures",*IEEE Trans. Circuits and Syst.*,Vol.35, pp. 936-946, 1988,

[21] P. Prommee, N. Sra-ium and K. Dejhan, "High-frequency log-domain current-mode multiphase sinusoidal oscillator," *IET Circuits Devices Syst.*, Vol. 4, Issue. 5, pp. 440–448, 2010.