Current and Voltage Mode Quadrature Oscillator Based on Voltage Differencing Buffered Amplifier

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ABSTRACT

In this work, we present a current-mode and voltage-mode quadrature oscillator circuit using a voltage differencing buffered amplifier (VDBA), two grounded capacitors, and a grounded resistor. The oscillation condition and frequency are orthogonally (or independently) controllable. The current-mode and voltage-mode quadrature signals can be simultaneously obtained from the proposed circuit. The use of only grounded capacitors and resistors makes the proposed circuits ideal for integrated circuit implementation. The quadrature oscillator is simulated with SPICE simulation program using 0.35-μm technology parameters.

Keywords: Quadrature oscillator, CMOS active elements, non-ideal analysis, voltage mode

Introduction

In the design of electronic systems, the need often arises both single periodic waveform and two periodic waveforms with 90° phase difference called a quadrature oscillator. Application areas of quadrature oscillator are in the communication system for quadrature mixers, in test and measurement system for testing characterizing electronic devices and circuits, in single-sideband generators or selective voltmeters [1, 2]. Different kinds of active elements have been used in quadrature oscillators up to now. Designers of quadrature oscillators utilize various active elements such as the positive, negative and inverting second generation current conveyor (ICCII-, CCII+, CCII-) [3-5], current differencing transconductance amplifier (CDTA) [6-8], current differencing buffered amplifier (CDBA) [9-10], operational amplifier [11], current feedback operational amplifier (CFOA) [12-14], differential difference current conveyor (DDCC) [15], fully balanced voltage differencing buffered amplifier (FB-VDBA) [16], also known as current backward transconductance amplifier (CBTA) [17], differential difference dual-X second generation current conveyor (DD-DXCCII) [18] and four terminal floating nullor (FTFN) [19-21].

A summary of the performance parameters of compared oscillators and the proposed oscillator are shown in Table 1. It can be observed from Table 1 that the proposed oscillator possesses superior features according to recently reported oscillators.

In this paper, voltage differencing buffered amplifier (VDBA) which is attractive active element contains two basic blocks like voltage buffer and transconductance stage which can be tuned electronically biasing current. Therefore, in this paper, the VDBA is chosen to be used in the design of an electronically tunable quadrature oscillator having two voltage outputs and three current outputs. Its main advantages are the minimum number of active and passive elements and independent setting of frequency and condition of oscillations. Besides, all passive elements are grounded and the required oscillator frequency could be easily adjusted by varying the external DC bias currents of the VDBAs.

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Table 1. Comparison of the proposed oscillator with those of previous circuits

	Number of active elements	Number of passive elements	Electronically adjusting oscillation condition independently of oscillation frequency	Types of passive elements' tie	Type (VM/CM) and number of outputs	Frequency of oscillation
Sobhy and Soliman (2007) [3]a	3 ICCII-	4R/2C	No	Grounded	2 VM	3.98 MHz
Khateb et al. (2012) [4]	2 CCII	3R/2C	No	Grounded	2 CM	10 kHz
Yucel and Yuce (2015)[5]	2 CCII-	4R/2C	No	Floating	3 VM	4.54 MHz
Horng et al. (2010) [6]b	3 CDTA	3C	Yes	Grounded	2 VM / 2 CM	410 kHz
Jin & Wang (2014) [7]	2 CDTA	1R/2C	Yes	Floating	4 CM	240 MHz
Jin and Wang (2012) [8]	1 CDTA	1R/2C	No	Floating	2 CM	1.87 MHz
Tangsrirat et al. (2008) [9]	2 CDBA	3R/2C	No	Floating	2 VM	15.91 kHz
Keskin (2005) [10]	1 CDBA	2R/2C	No	Floating	1 VM	795.8 Hz
Horng (2011) [11]c	3 OP-AMP	5R/3C	No	Floating	2 VM	15.91 kHz*
Tangsrirat & Surakamponton (2009) [12]	2 CFOA	3R/2C	No	Floating	2 VM	15.8 kHz
Lahiri et al. (2013) [13]d	3 CFOA	4R/2C	No	Floating	1 VM/2 CM	128.9 kHz
Soliman (2000) [14]e	1 CFOA	2R/2C	No	Floating	1 VM	160.9 kHz
Soliman (2000) [14]f	2 CFOA	2R/2C	No	Grounded	2 VM	153.43 kHz
Kumngern & Dejhan (2009) [15]	2 DDCC	3R/2C	No	Grounded	2 VM	640 kHz
Yesil et al. (2016) [16]	1 FB-VDBA	1R/2C	No	Floating	2VM	1.33 MHz
Ayten et al. (2012) [17]g	1 CBTA	1R/2C	No	Grounded	2 VM/1CM	18.9 MHz
Chaturvedi, & Mohan (2015) [18]	1 DD-DXCCII	3R/2C	No	Grounded	3VM/2CM	15.78 MHz
Bhaskar and Senani (2005) [19]	2 PFTFN	4R/2C	No	Floating	1 CM	17.36 kHz*
Kumar and Senani (2007) [20]	1 PFTFN	5R/2C	No	Floating	1 VM	4.98 kHz
Cam et al. (2000) [21]i	1 FTFN	5R/2C	No	Floating	1 CM	28 kHz
The proposed oscillator	2 VDBA	1R/2C	Yes	Grounded	2 VM/3 CM	1.14 MHz

aFigure 8a in [3], bThird order QO, cFigure 1 in [11], dFigure 1a in [13], eFigure 1 in [14], fFigure 2 in [14], gFigure 3 in [17], i 2. circuit in Table-1 in [21], *theoretical result of FO; VM: voltage-mode; CM: current-mode; ICCII: inverting second generation current conveyor; CCII: second generation current conveyor; CDTA: current differencing transconductance amplifier; CDBA: current differencing buffered amplifier; OPAMP: operational amplifier; CFOA: current feedback operational amplifier; DDCC: differential difference current conveyor; FB-VDBA: fully balanced voltage differencing buffered amplifier; CBTA: current backward transconductance amplifier; DD-DXCCII: differential difference dual-X second generation current conveyor; FTFN: four terminal floating nullor; VDBA: voltage differencing buffered amplifier

Voltage Differencing Buffered Amplifier

In the paper [22], the schematic symbol of the VDBA is added ZC- terminals, which is negative of the Z terminal. Its modified schematic symbol of the VDBA is given in Figure 1.

Using standard notation, the relationship between port currents and voltages of the VDBA can be defined by the following hybrid matrix:

$$\begin{pmatrix} I_P \\ I_N \\ I_Z \\ I_{ZC-} \\ V_W \end{pmatrix} = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ g_m & -g_m & 0 \\ -g_m & g_m & 0 \\ 0 & 0 & \alpha \end{pmatrix} \begin{pmatrix} V_P \\ V_N \\ V_Z \end{pmatrix} \quad (1)$$

where g_m and α represent transconductance and the non-ideal voltage gain of the VDBA, respectively. The value of α in an ideal VDBA is equal to unity. It should be noted from the above

Figure 1. The circuit symbol of the VDBA

Figure 2. Proposed quadrature oscillator circuit
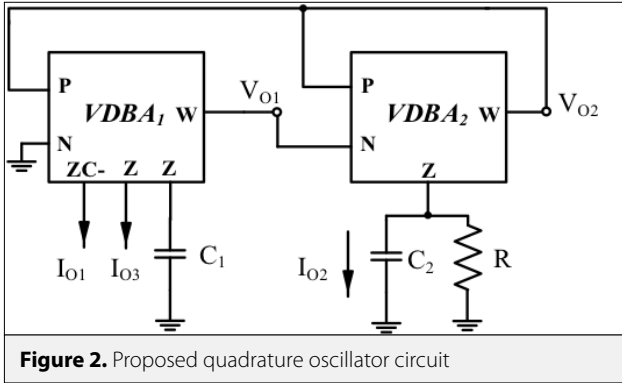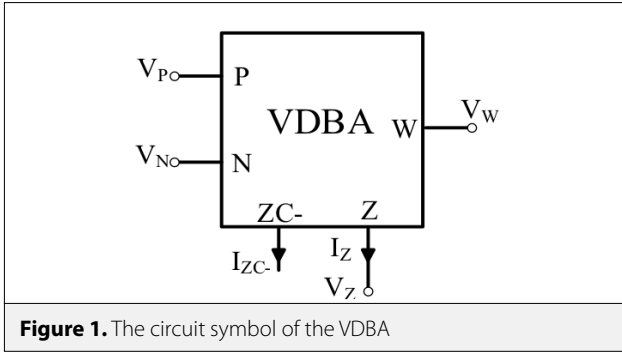
that it possesses W terminal of low impedance and other terminals of high impedance. The CMOS implementation of the VDBA consists of an operational transconductance amplifier and a voltage buffer. The current of P and N are approximated to zero. The terminal W is the output of voltage buffer; thus the voltage of W is approximated to Z.

Proposed Quadrature Oscillator Circuit

The proposed quadrature oscillator which is shown in Figure 2 offers two voltage outputs and three current outputs. It is made up of two VDBAs and three passive elements such as two grounded capacitors and a resistor.

The circuit analysis yields the following second order characteristic equation.

$$s^2 C_1 C_2 + s C_1 (\frac{1}{R} - g_{m2}) + g_{m1} g_{m2} = 0 \qquad (2)$$

The frequency of oscillation (FO) and the condition of oscillation (CO) are found as

$$FO : f_0 = \frac{1}{2\pi} \sqrt{\frac{g_{m1} g_{m2}}{C_1 C_2}} \qquad (3a)$$

$$CO : \quad R.g_{m2} = 1 \qquad (3b)$$

It is apparent that FO and CO can be set independently. The relation between the two output voltages at the oscillation frequency is

$$V_{O1} = e^{-j90°} V_{O2} k_{VM} ; \qquad k_{VM} = \sqrt{\frac{g_{m1} C_2}{g_{m2} C_1}} \qquad (4)$$

This confirms that the output voltages are in quadrature and indicates that if the output voltage amplitudes are to be equal, we must choose $k_{VM}=1$. At the oscillation frequency it holds for the three output currents;

$$I_{O1} = e^{j90°} I_{O2} k_{CM} = e^{j180°} I_{O3} ; \qquad k_{CM} = \sqrt{\frac{g_{m1} C_1}{g_{m2} C_2}} \qquad (5)$$

The currents are not only shifted by 90° but also shifted by 180° and they have the same amplitude if $k_{CM}=1$ abstract

Non-Ideal and Parasitic Effects Analyses

Considering the non-ideal voltage gain α of the VDBA, the second order characteristic equation in Equation (2) convert to:

$$s^2 C_1 C_2 + s C_1 (\frac{1}{R} - g_{m2} \alpha_2) + g_{m1} g_{m2} \alpha_1 \alpha_2 = 0 \qquad (6)$$

and non-ideal FO and the CO are given as:

$$FO : f_0 = \frac{1}{2\pi} \sqrt{\frac{g_{m1} g_{m2} \alpha_1 \alpha_2}{C_1 C_2}} \qquad (7a)$$

$$CO : \quad R.g_{m2} = \alpha_2 \qquad (7b)$$

From Equations (7a) and (7b), the tracking errors slightly change the FO and CO. However, the FO and CO still can be adjusted. Also, the non-ideal relation between the two output voltages at the oscillation frequency is

$$V_{O1} = e^{-j90} k_1 V_{O2} ; \quad k_1 = \sqrt{\frac{g_{m1} C_2 \alpha_1}{g_{m2} C_1 \alpha_2}} \qquad (8)$$

It is clear from equation (8) that the phase difference between V_{O1} and V_{O2} is -90° under the sinusoidal steady state. In other words, its output voltages are in quadrature. It is seen from Equation (8) that the output voltages have to equal to amplitude for $k_1=1$. The non-ideal relationships among the current outputs are also given below at Equation (9);

$$I_{O1} = e^{j90} k_2 I_{O2} = e^{j180} I_{O3} ; \quad k_2 = \sqrt{\frac{g_{m1} C_1 \alpha_2}{g_{m2} C_2 \alpha_1}} \qquad (9)$$

Similarly, It is obvious from Equation (9) that not only the outputs of current have to equal to amplitude for $k_2=1$ but also phase difference among the current outputs are 90°. Note that, in order to obtain the I_{O2} current output through the capacitor, CCII- can be easily preferred by grounding Y terminal and using X and Z as input and output, respectively. By taking into account the parasitic effects of the VDBA, Figure 3 depicts parasitic effects of the proposed quadrature oscillator circuit.
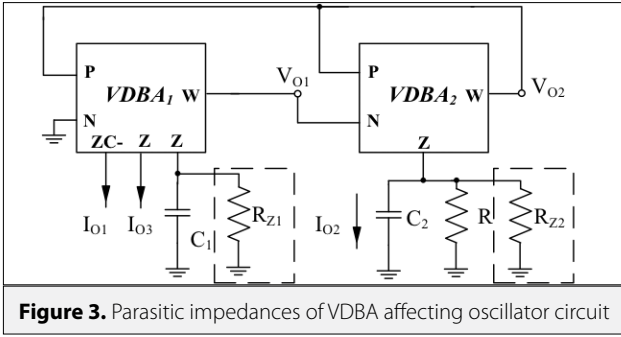
Figure 3. Parasitic impedances of VDBA affecting oscillator circuit

R_{Z1} and R_{Z2} are the parasitic resistance of Z terminal of VDBA which belongs i[th] the VDBA. R_{Z1} and R_{Z2} are the mainly parasitic elements for the proposed oscillator circuit. Reanalyzing the oscillator circuit shown in Figure3 yields the following modified second order characteristic equation;

$$s^2 C_1 C_2 + s(\frac{C_1}{R//R_{Z2}} + \frac{C_2}{R_{Z1}} - C_1 g_{m2})...$$

$$+ g_{m1} g_{m2} + \frac{1}{R_{Z1} R_{Z2} // R} - \frac{g_{m2}}{R_{Z1}} = 0 \qquad (10)$$

The parameter of the modified FO and the modified CO can be expressed as follows;

$$FO: f_0 = \frac{1}{2\pi}\sqrt{\frac{g_{m1}g_{m2}}{C_1 C_2} + \frac{1}{C_1 C_2 R_{Z1} R_{Z2} // R} - \frac{g_{m2}}{C_1 C_2 R_{Z1}}} \qquad (11a)$$

$$CO: \quad C_1 g_{m2} = \frac{C_1}{R//R_{Z2}} + \frac{C_2}{R_{Z1}} \qquad (11b)$$

The value of the modified FO and CO may be altered slightly by parasitic effects of VDBA. To minimize the deviation of the FO, output resistance of Z terminal of the VDBA should be increased by using cascode current mirror for the first stage of VDBA.

Simulation Results

So as to confirm the theoretical results of the proposed quadrature oscillator circuit, Figure 2 has been simulated using SPICE simulation program. According to previous version [22], the modified CMOS implementation of VDBA is depicted in Figure 4. The aspect ratios of the CMOS transistors used in the modified VDBA are given in Table 2.The supply voltages, biasing voltage and current are chosen as $V_{DD}=-V_{SS}=1.5V$, $V_B=-0.9V$, and $I_B=100\mu A$.

Table 2. Transistors aspect ratios for the modified VDBA

Transistors	W(μm)	L(μm)
M_1-M_4, M_{18}-M_{21}	7	0.35
M_5- M_8	21	0.7
M_9-M_{12}	7	0.7
M_{13}-M_{14}	3.5	0.7
M_{15}-M_{17}	14	0.35

VDBA: voltage differencing buffered amplifier

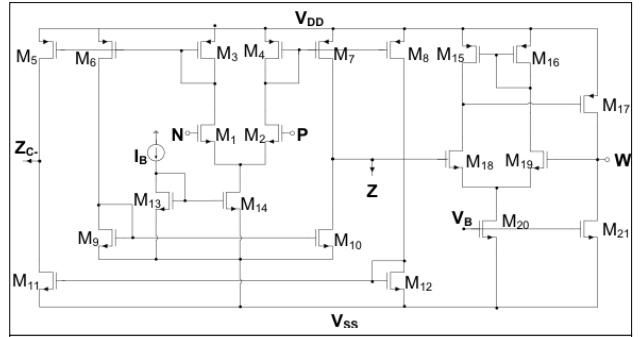**Figure 4.** The modified CMOS structure for the VDBA

The quadrature oscillator has been built with $C_1=C_2=100pF$, $g_{m1}=g_{m2}=735\mu A/V$ and $R=1.4k\Omega$ which is slightly bigger than the value $1.36k\Omega$ calculated from CO. This is to ensure that oscillations would start. The theoretical FO is calculated as $f_0=1.17MHz$. The simulated FO obtained from the simulation results is measured as 1.14MHz. the slightly discrepancy between simulation and theoretical resutls stems from limited frequency bandwidth of the transconductance and voltage transfer gain error, and parasitic effects. The simulated output waveforms of the quadrature voltages are demostrated in Figure 5, whereas Figure 6 depicts the spectrum of the oscillator output voltages. As it is seen from Figure 6, voltage outputs, V_{O1} and V_{O2}, of the proposed oscillator provide 52.2dB and 48.1dB of rejection at the second harmonic, respectively.
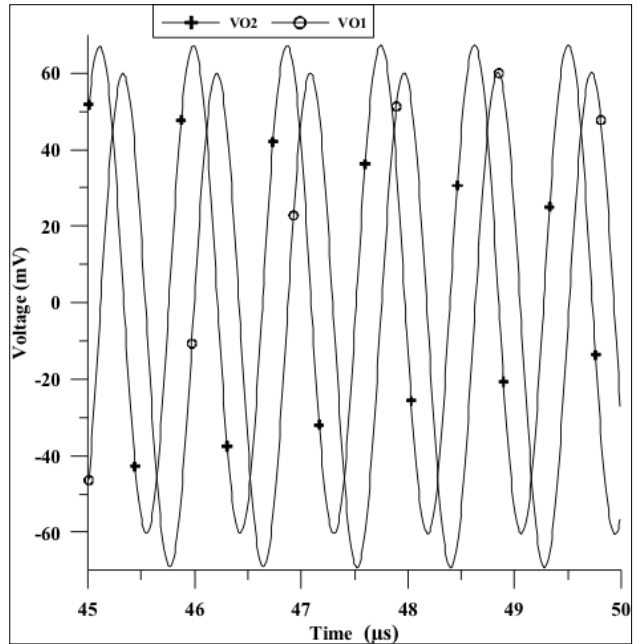

Figure 5. The steady-state waveforms for the quadrature voltages V_{O1} and V_{O2}

The waveforms of the oscillator output currents are illustrated in Figure 7, whereas Figure 8 depicts the spectrum of the
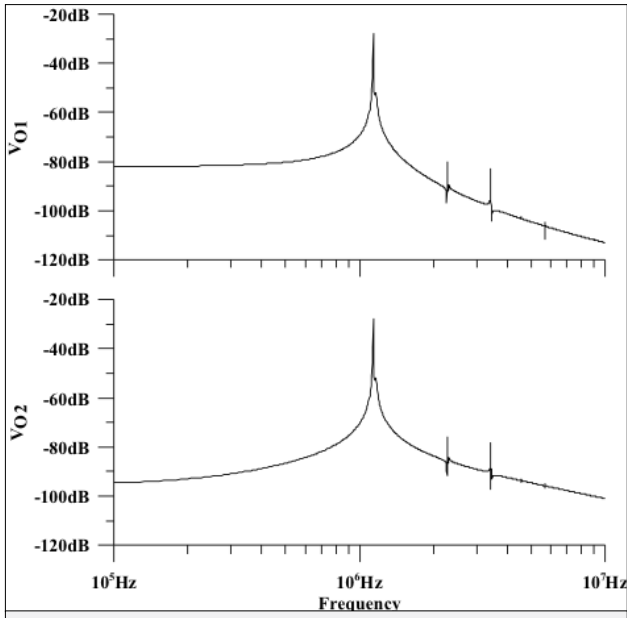
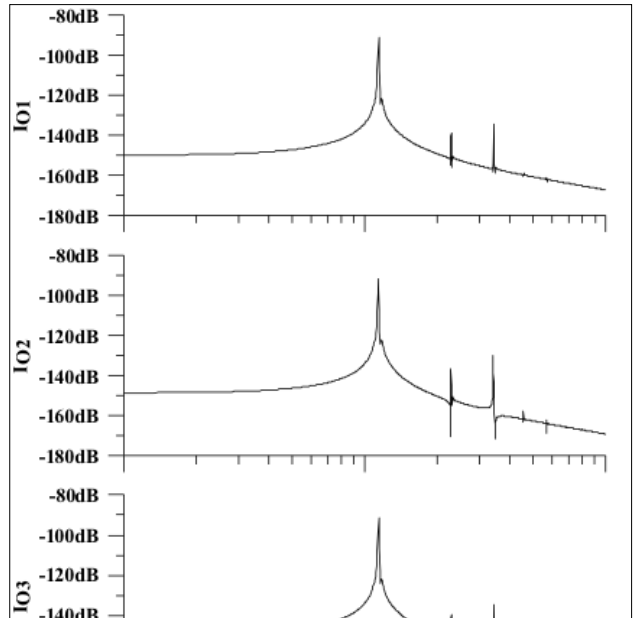**Figure 6.** Frequency spectrums of outputs V_{O1} and V_{O2}

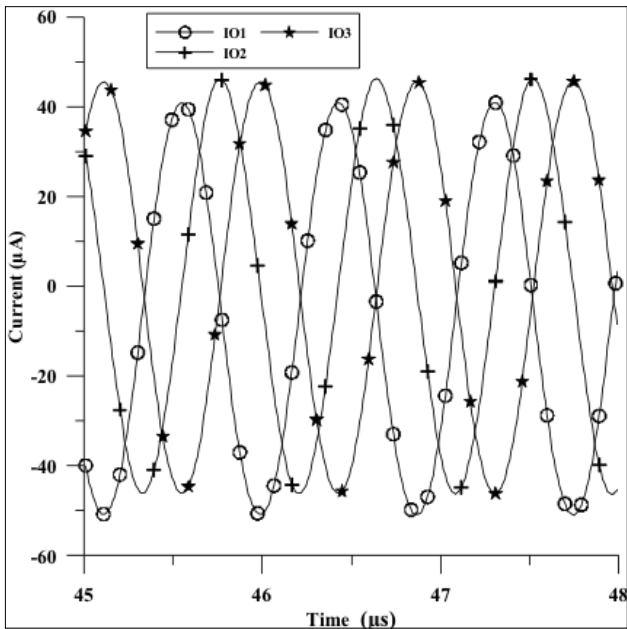**Figure 8.** Frequency spectrums of outputs I_{O1}, I_{O2}, and I_{O3}

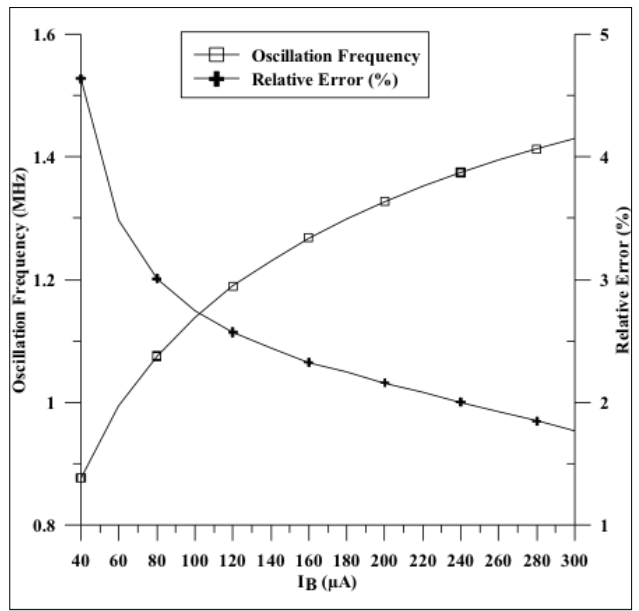**Figure 7.** The steady-state waveforms for the quadrature currents I_{O1}, I_{O2}, and I_{O3}

Figure 9. Variations of oscillation frequency and relative error via IB biasing current

oscillator output currents. As it is seen from Figure 8, second harmonic rejection ratios of current outputs, I_{O1}, I_{O2}, and I_{O3} are around 47.4dB, 45dB, and 48.5dB, respectively. The total harmonic distortion (THD) is 0.33% for voltage output V_{O1}, 0.52% for voltage output V_{O2}, 0.87% for current output I_{O1}, 1.4% for current output I_{O2} and 0.84% for current output I_{O3}.

In order to change electronically oscillation frequency, transconductance value (g_{m1}) of first VDBA element is tuned by the means of I_B biasing current. Variation of between oscillation frequency and I_B biasing current is given in Figure9. Moreover, the definition of percentage relative error can be described by the following equation;

$$\% Relative\ Error = 100\frac{f_{Theoretical} - f_{Simulation}}{f_{Theoretial}} \quad (12)$$

Variation of between I_B biasing current and percentage relative error value is also depicted in Figure9. It can be observed from Figure 9 that percentage relative error is decreased with increasing biasing current (I_B).
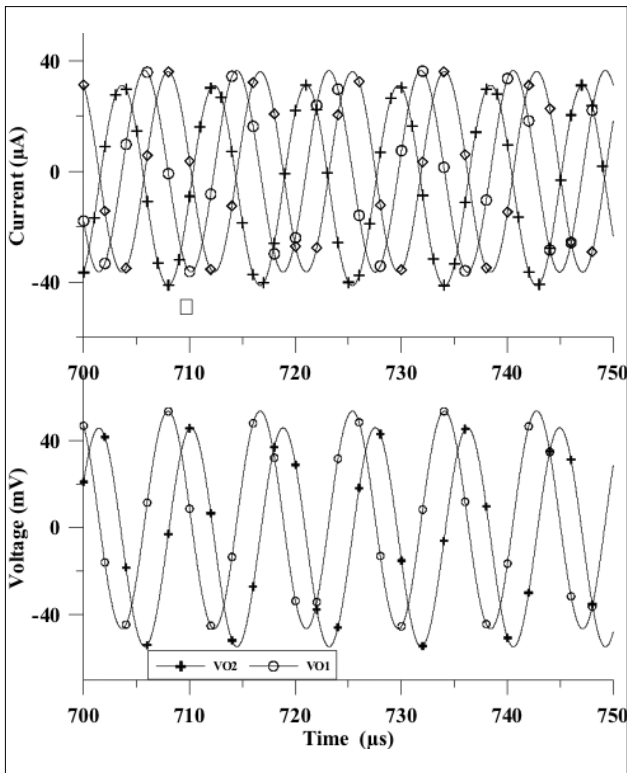
Figure 10. The steady-state waveforms for voltage and current outputs

So as to survey the performance of the proposed quadrature oscillator at low frequencies, external capacitances values are chosen as 1nF to obtain frequency oscillation of f_0=114 kHz. The steady-state waveforms for voltage and current outputs are depicted in Figure 10. THDs of voltage outputs (V_{O1} and V_{O2}) are calculated as 0.23% and 0.35%, respectively, whereas THDs of current outputs (I_{O1}, I_{O2}, and I_{O3}) are calculated as 0.58%, 0.89%, and 0.56%, respectively.

The behaviors of the CMOS implementation of VDBA in Figure 4 with respect to capacitors and resistor have been appreciated with the help of statistical analysis results by using the well-known Monte Carlo analysis. Monte Carlo simulation is carried out one hundred times for proposed oscillator circuit in Figure 2. The Monte Carlo analyses having 5% Gauss deviation of capacitors and 1% Gauss deviation of the resistor are obtained as in Figure 11 where FO and THD of V_{O1} variations of the proposed oscillator circuit in Figure 2 are given.

Conclusions

New electronically tunable quadrature oscillator having a minimum number of active and passive elements is presented. It based on VDBA exhibits two voltage outputs and three current outputs. The influence of non-ideal effects of the VDBAs on the oscillator functionality has been investigated. Furthermore,
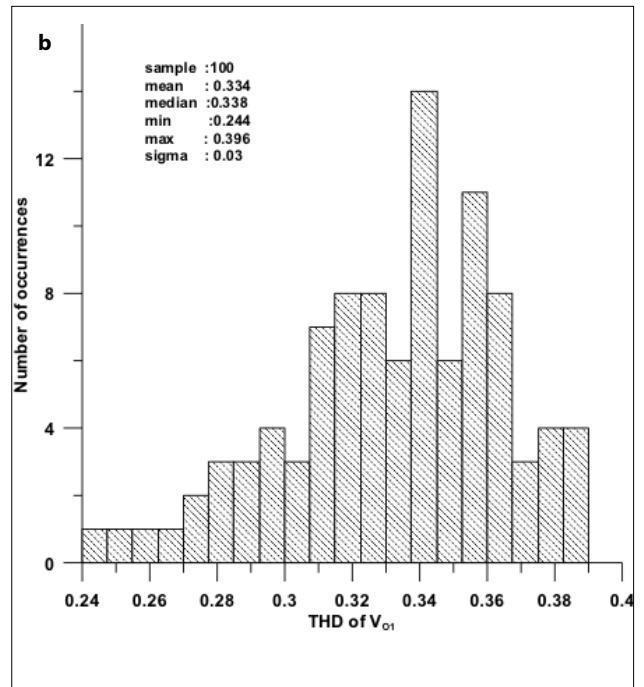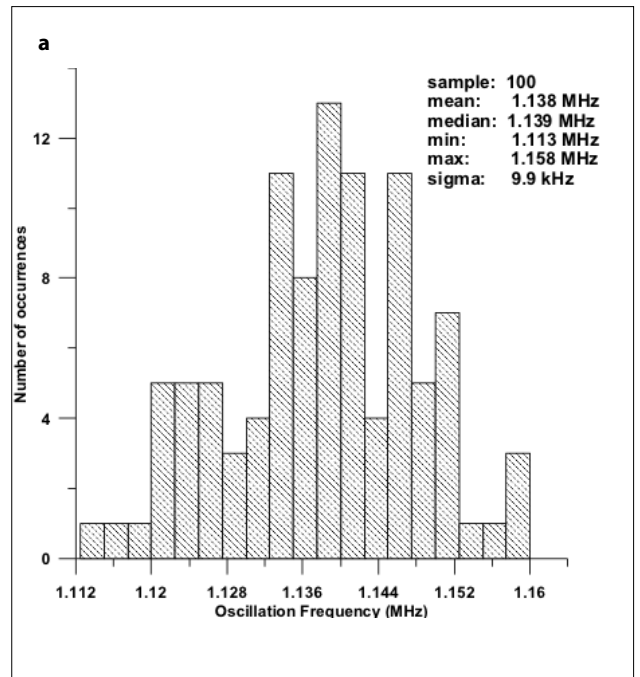

Figure 11. The histograms of (a) FO and (b) THD of VO1 distribution of the proposed oscillator circuit (100 times Monte Carlo Simulation)

the behaviors of the CMOS implementation of VDBA in Figure 4 with respect to passive elements have been evaluated and variation of between oscillation frequency and biasing current has also been given. It is easily observed simulation results that the proposed circuit enjoys low THD, feasibility of circuit and adjustment in a wide range.

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