Multiphase Sinusoidal Oscillators Using Operational Transconductance Amplifiers

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Abstract

A multiphase sinusoidal oscillator using multiple-output operational transconductance amplifiers and grounded capacitors is described. The proposed multiphase sinusoidal oscillator is composed of *N* cascaded lossy integrators, which can generate *N* output current equal-amplitude signals that are equally spaced in phase. The oscillation frequency can be electronically tunable without affecting the condition of oscillation. The proposed configuration also has a simple structure, low component count, low active and passive sensitivities, and is very suitable for IC implementation in both bipolar and CMOS/BiCMOS technologies. The theoretical results are verified by PSPICE simulation. Simulation results show that a multiphase sinusoidal oscillator can generate a high frequency sinusoidal waveform.

Keywords: Current-mode; electronically tunable; multiple-output OTA; multiphase sinusoidal oscillator

1. Introduction

An operational transconductance amplifier (OTA) is a fundamental building block of analogue circuits and systems. The OTA provides a highly linear electronic tunability, a wide tunable range and a powerful ability to generate various circuits. Moreover, OTA-based circuits require no resistors and, therefore are suitable for IC implementation [1]-[6].

Multiphase sinusoidal oscillators (MSOs) have wide applications in communication, signal processing, power controlled systems. In the past, a number of MSO circuits based on different design techniques are available in the literature [7]-[19]. Early systems of the MSOs by Kaplan and Bachar [7], Rahman and Haque [8], Ramamurti and Ramaswami [9], Mikhael and Tu [10] exhibit good performance, but those circuits suffer from complex structures and use of large numbers of both active and passive elements. Simpler circuits are available for an MSO based on the active-R technique [11]-[12], but they lack the electronic tunability. Although an OTA-based MSO by Khan *et al.* [13] has a simple structure as well as electronic tunability, it suffers from limited output voltage swings, operating range and temperature sensitivity. Additionally, circuits composed by OTA in [13] require a large number of components and also need buffers to reduce the high output impedance associated with transductance amplifiers. These make the circuits limited to OTAs that are on chip buffers that are already available with some OTAs, e.g., LM 13600, LM13700. Hou and Shen [14] and Wu *et al.* [15] proposed second-generation current conveyors (CCIIs) based MSOs that use a single CCII per phase. However, a junction field-effect transistor (JFET) and three current conveyors are required for each phase in order to achieve electronic tenability [15]. Another MSO using current feedback operational amplifier (CFOA) is described by Wu *et al.* [16] to generate an MSO that operates at relatively high frequencies, but their approach requires access to the amplifier compensation terminal. This requirement is very restrictive since only one such CFOA like the AD844 is current available. The simple structure operational amplifiers based realization by Gift in [17]-[18] has large output voltage swings, but it suffers from the use of many external passive components and a number of them float. Furthermore, both circuits lack the electronic tunability.

Recently, a new technique for realizing MSO using second-generation current controlled current conveyors (CCCIIs) was proposed [19]. The circuit exploits the parasitic resistance of the CCCIIs which make electronic tunability possible. However, the implementation scheme is only suitable for bipolar technology.

In this paper, we present a new electronically tunable multiphase sinusoidal oscillator using multiple-output operational transconductance amplifiers (multiple-output OTAs). The proposed structures yield the following features:

- The proposed MSO uses the number of active and passive components that are roughly equal to the CCCII-based MSO of Abuelma'atti and Al-Qahtani [19]. However, the proposed MSO configuration is suitable to implement in both bipolar and CMOS technologies and generates a high frequency sinusoidal waveform. Whereas, the previous CCCII-based MSO scheme is only suitable for bipolar technology and does not generate a sinusoidal waveform at high frequency. This shows that the proposed MSO is more flexible for IC implementation and dealing with applications than the previous CCCII-based MSO.
- The proposed MSO uses two grounded capacitors and one OTA per phase, whereas the OTA-based electronically tunable MSO scheme of Khan *et al.* [13] used one grounded capacitor, two ungrounded resistors and one OTA (or one grounded capacitor and two ungrounded capacitors and one OTA) per phase, therefore, the proposed MSO is more suitable for IC fabrication than the MSO structure in [13].
- The proposed MSO provides high-output impedance current sources, whereas the low-output impedance voltage source of MSO presented in [13] requires additional voltage followers, of which some OTAs, e.g., LM13600, LM13700 are available. Therefore the proposed structure is more flexible for applications than the MSO in [13].
- The oscillation frequency can be electronically controlled without disturbing the condition of oscillation and vice versa.
- The proposed MSO circuit uses a multiple-output OTA and two grounded capacitors per section which can provide odd and even-phase output currents.
- The proposed MSO configuration is simple and uses only grounded capacitors without external resistors. Thus, it is very suitable for IC fabrication [20].

2. Circuit realization

2.1. Operational transconductance amplifier

Fig. 1 shows the symbol of the multiple-output OTA. An ideal OTA is a finite bandwidth voltage-controlled current source, with an infinite input and output impedance. The output current of the ideal multiple-output OTA is given by:

$$I_o = \pm g_m (V_+ - V_-) \qquad (1)$$

where g_m is the transconductance gain, I_o is the output current and V_+,V_- are the non-inverting and inverting input voltages. If the OTA in Fig. 1 is implemented with MOS transistors operated in the saturation region, the transconductance (g_m) is proportional to $\sqrt{I_{abc}}$ and if it is implemented with bipolar transistors, the g_m is directly proportional to I_{abc}.

By using the multiple-output OTA, the basic building block of the proposed MSO circuit is shown in Fig. 2. It consists of a multiple-output OTA and two grounded capacitors. The transfer functions between the output and input terminal of the circuit in Fig. 2 can be expressed by:

$$\frac{I_2}{I_1} = \frac{\pm C_2/C_1}{1 + s(C_2/g_m)} \qquad (2)$$

From (2), note that the circuit in Fig. 2 is the lossy integrator, which can be the inverting and the non-inverting lossy integrators inserted into a single circuit. The lossy integrator in Fig. 2 is used to realize two MSO circuits.

2.2.Odd-phase sinusoidal oscillator circuit

Fig. 3 shows the proposed odd-order multiphase sinusoidal oscillator. It consists of *N* cascaded inverting lossy integrators. Each block uses two plus-type output terminals and two minus-type output terminals of the OTA. Using (2), the loop-gain between points x and y of the scheme of Fig. 3 can be expressed for N sections by:

$$\frac{y}{x} = \left(\frac{-C_2/C_1}{1 + s(C_2/g_m)} \right)^N \qquad (3)$$

The system can be set to provide a sinusoidal oscillation, if the loop gain is unity:

$$\left(\frac{-C_2/C_1}{1 + s(C_2/g_m)} \right)^N_{S=j\omega_o} = 1 \qquad (4)$$

or

$$(1 + j\omega_o C_2/g_m)^N + (-1)^{N+1}(C_2/C_1)^N = 0 \qquad (5)$$

Equation (5) is the characteristic equation for an *N*-th order multiphase sinusoidal oscillator of Fig. 3. By expanding (5), it can be shown that the scheme in Fig. 3 is only for odd numbers of *N*. By equating the imaginary and real parts of (5) to zero, the frequency of oscillation and condition of oscillation for various odd values of *N* (N=3, 5, 7,····) can be obtained in Table 1. The outputs at each of the stages of the scheme are symmetrical, i.e. equal in amplitude and equally spaced in phase at the frequency of oscillation. By using Table 1, the oscillation frequency and condition of a three-phase sinusoidal oscillator (*N*=3) can be achieved as:

$$f_o = \frac{1.737 g_m}{2\pi C_2} \qquad (6)$$

and

$$\frac{C_2}{C_1} = 2 \qquad (7)$$

From Table 1, it can be seen that the frequency of oscillation and condition of oscillation can be orthogonally controllable. The condition of oscillation can be adjusted with the capacitor C_1. The oscillation frequency can be tuned electronically with the transconductance g_m through the bias current I_{abc}. The high frequency oscillation can be generated without the effect of OTA bandwidth in terms of the conditions of oscillation. Since the output impedances of the OTAs are very high, the MSO current outputs can be directly connected to the next stage without using additional current followers. From (6), the active and passive sensitivities of the proposed MSO circuit are low, approximately -1 to 1. The use of multiple-output OTA provides an inverted version of the output current, hence there are 2*n*=6, 10, 14,····, even-phase available output currents. Therefore, the scheme in Fig. 3 can generate odd-order and some even-order multiphase sinusoidal oscillators.

2.2. Even/odd-phase sinusoidal oscillator circuit

Fig. 4 shows the proposed even-order multiphase sinusoidal oscillator. The third stage is a first-order inverting lossy integrator that uses two plus-type output terminals and two minus-type output terminals of the OTA, while the other basic building blocks for this scheme are the identical, non-inverting lossy integrators that use the three plus-type output terminals and one minus-type output terminal of the OTA. Using (2), the loop-gain between the point x and y of the scheme of Fig. 4 can be expressed for *N* sections by:

$$\frac{y}{x} = -\left(\frac{C_2/C_1}{1+s(C_2/g_m)}\right)^N \tag{8}$$

The system can be set to provide a sinusoidal oscillation, if the loop gain is unity:

$$-\left(\frac{C_2/C_1}{1+s(C_2/g_m)}\right)^N_{S=j\omega_o} = 1 \tag{9}$$

or

$$\left(1+j\omega_o C_2/g_m\right)^N + \left(C_2/C_1\right)^N = 0 \tag{10}$$

Equation (10) is the characteristic equation for an *N*-th-order even/odd phase sinusoidal oscillator. By rearranging (10) and equating the imaginary and real parts to zero, the frequency of oscillation and the condition of oscillation can be obtained. The results are shown in Table 2. It is easy to show that, at the frequency of oscillation, $N\geq3$ equal amplitude equally spaced in-phase output currents can be obtained. From (10), it can clear that the MSO in Fig. 4 can generate odd-number or even-number of phases into a single system. The use of multiple-output OTA provides an inverted version of the output current.

3. Simulation results

For the theoretical analysis of the proposed multiphase sinusoidal oscillator, a CMOS design example has been simulated through the PSpice simulation program. The PSpice model parameters for NMOS and PMOS transistor are listed in Table 3. The multiple-output plus/minus OTA are shown in Fig. 5. This schematic is modified from a well known single-ended OTA structure [21]. It consists of a source-coupled pair with identical MOS devices (M1-M2) operating in the saturation region [22] where the output current is replicated using the current mirrors. The MOS transistors aspect ratios are listed in Table 4 and the power supply is $V_{DD}=-V_{SS}=2.5V$. Fig. 6 presents the simulation results of the three-stage (*N*=3) sinusoidal oscillator in Fig. 3 with C_1=10pF, C_2=20.12pF, I_{abc}=250μA (g_m=0.371mS) for *n*=3 where C_2 was designed to be larger than 2 times C_1 to ensure the oscillation will start. Fig. 7 shows the sinusoidal waveform for *n*=6. Fig. 8 presents the simulation results of oscillation frequency of Fig. 3 by varying the value of the bias current I_{abc} (i.e. 50μA to 500μA or equal g_m from 0.1928mS to 0.48mS) with C_1=10pF and C_2=20.12pF. The relationship between C_2 and oscillation frequency is shown in Fig. 9. Fig. 10 shows the output currents against varied bias current I_{abc}. It shows that the

MSO can generate a frequency up to 10MHz agreeing with theory. However, the circuit generates a frequency higher than 10MHz, but the simulation results do not agree with theory. This error is caused by the parasitic capacitance of OTAs.

4. Conclusions

In this paper, a new electronically tunable MSO circuit has been presented. The proposed MSO has a simple configuration which uses a multiple-output OTA and two grounded capacitors per section. The MSO circuit is configured to provide an odd-number of equal-amplitude equally special in-phase output current. The oscillation condition and oscillation frequency are independently controlled. The proposed MSO has a simple structure and is electronically tunable and suitable for both CMOS and bipolar IC implementation. Simulation results, which confirm the theoretical analysis, are obtained. With respect to the MSO in [13], the proposed structure is more suitable for IC fabrication than the previous structure. With respect to the electronic-controlled MSO in [19], the proposed structure is more flexibility for implementation than the structure in [19].

5. References

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Captions

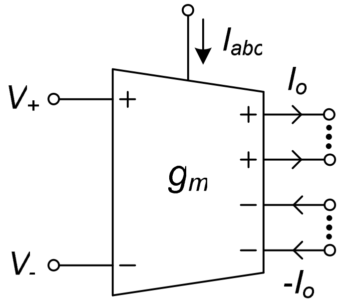

Fig. 1. Circuit symbol of the multiple-output OTA.

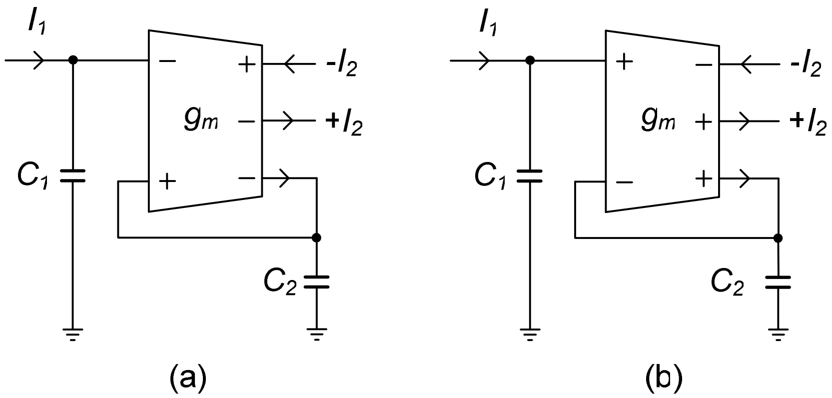

Fig. 2. Basic building block of proposed multiphase phase sinusoidal oscillator.

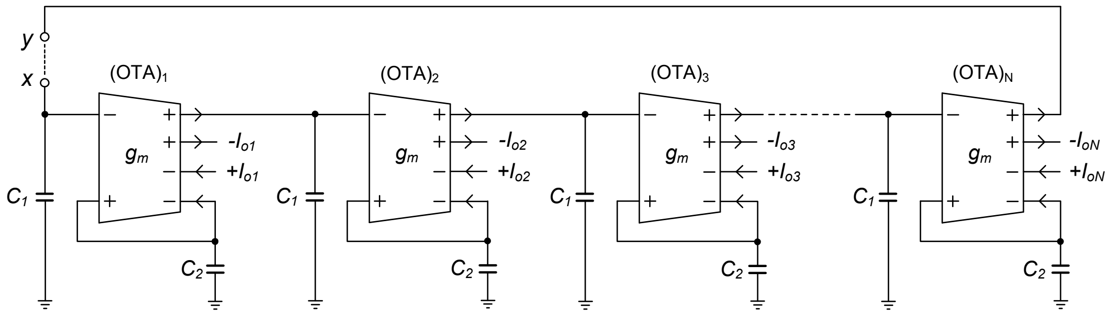

Fig. 3. Proposed odd-phase sinusoidal oscillator.

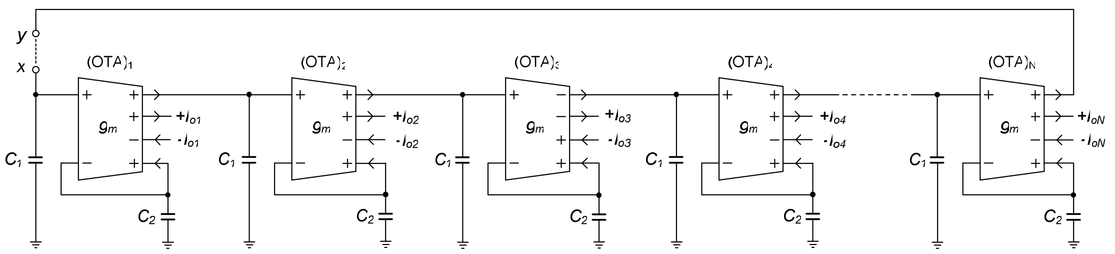

Fig. 4. Proposed odd-phase sinusoidal oscillator.

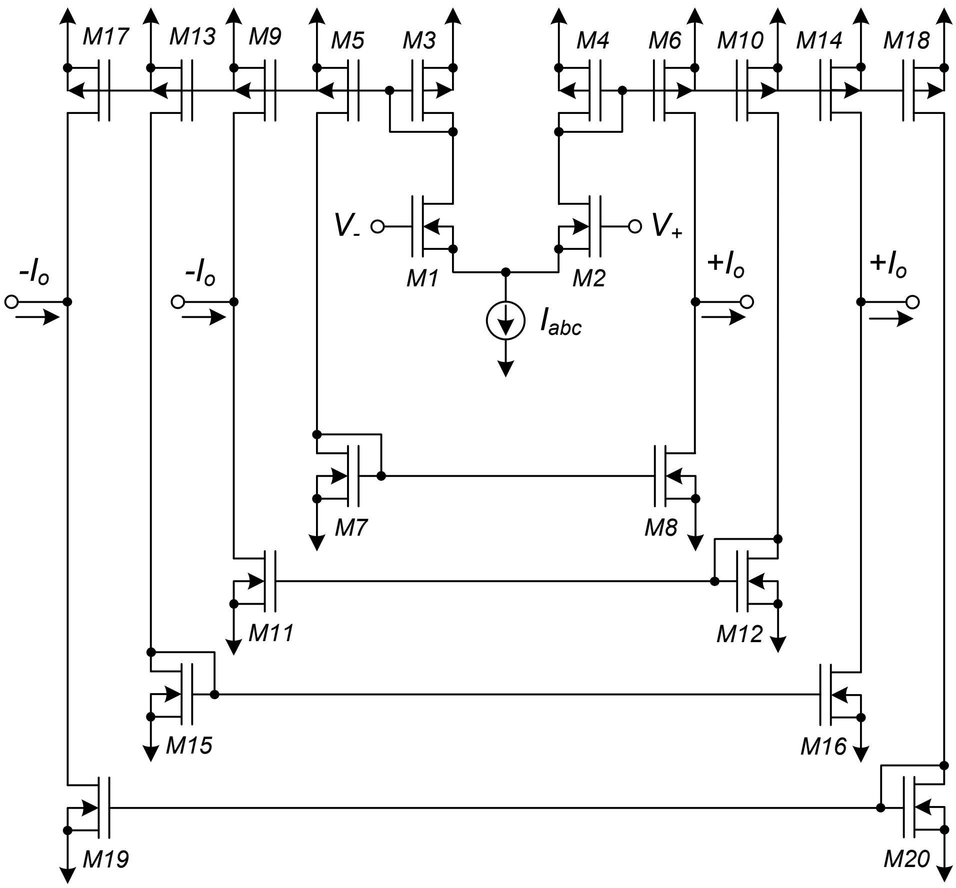

Fig. 5. CMOS multiple-output OTA implementation used in simulation.

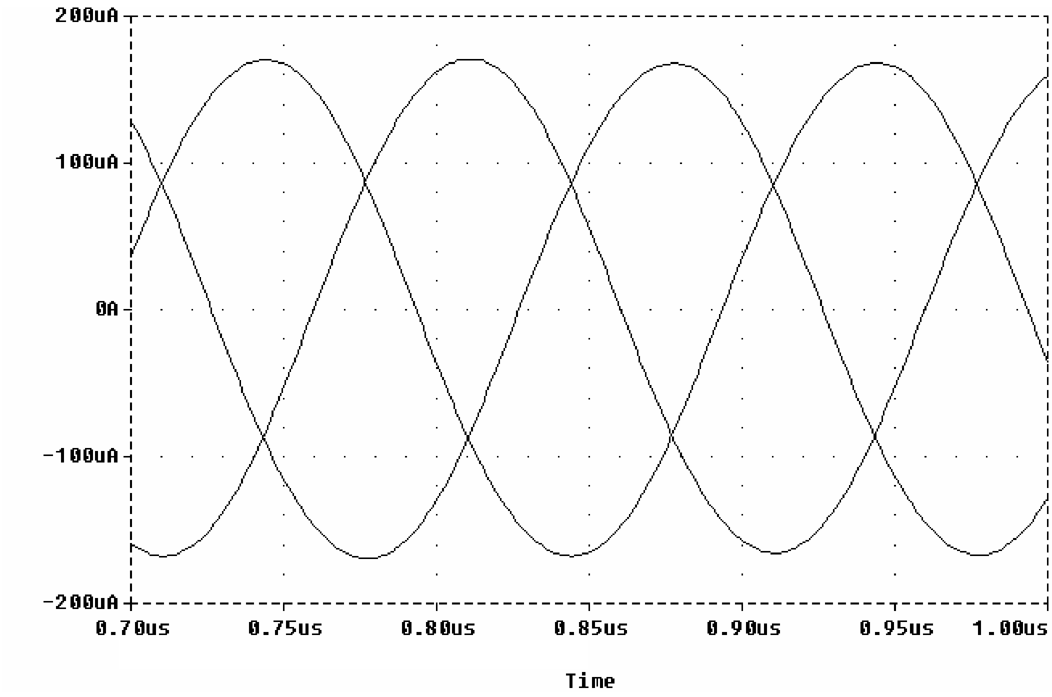

Fig. 6. Output waveform of three phase oscillator with C_1=10pF, C_2=20.12pF and bias currents=250μA.

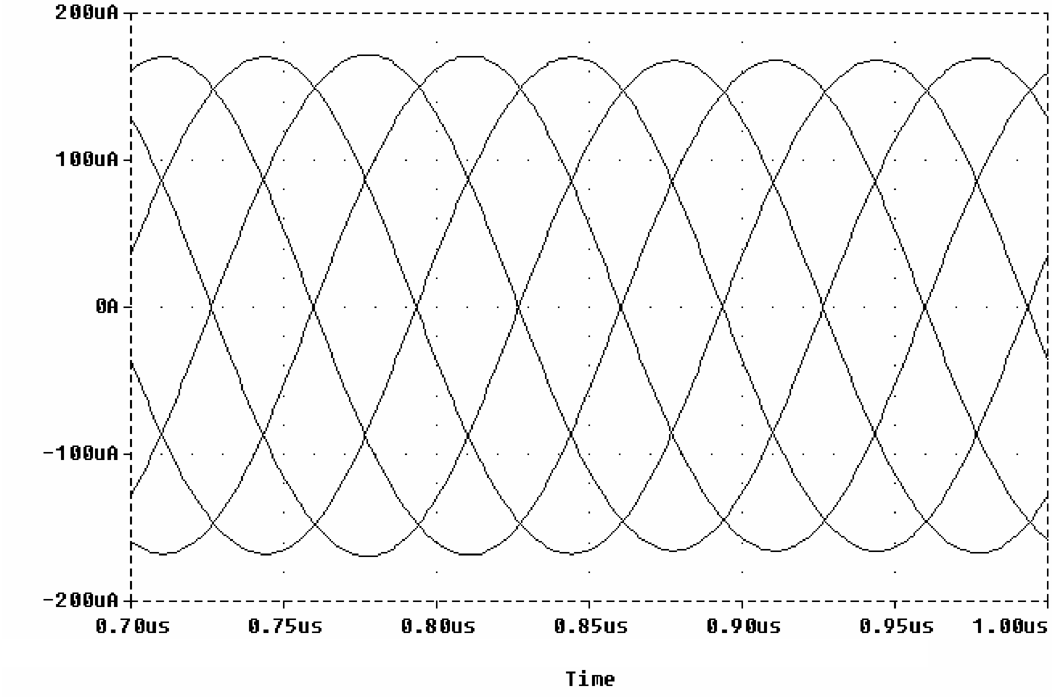

Fig. 7. Output waveform of six phase oscillator with C_1=10pF, C_2=20.12pF and bias currents=250μA.

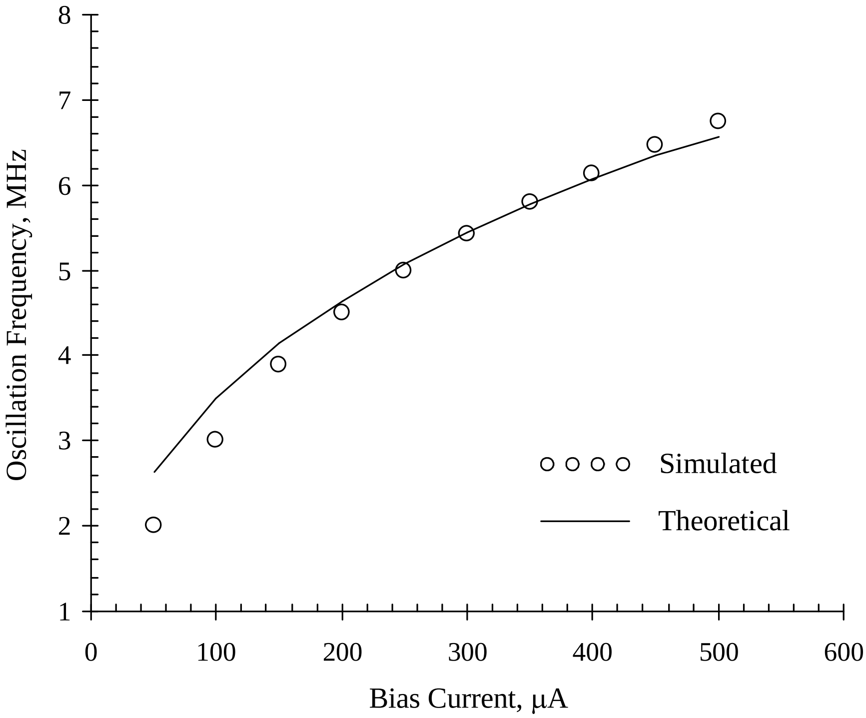

Fig. 8. Variation of the oscillation frequency with the bias current with C_1=10pF and C_2=20.12pF

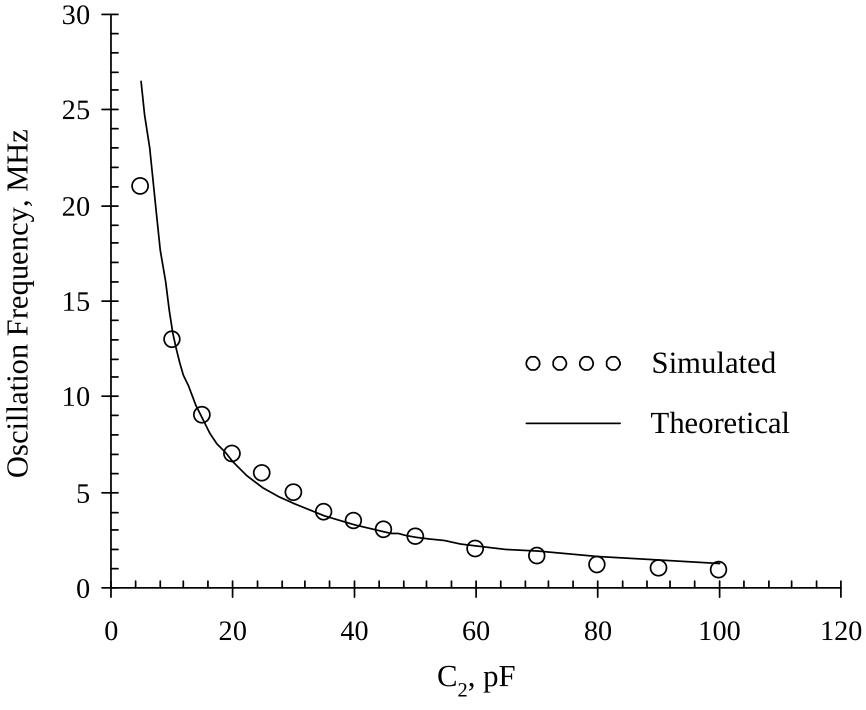

Fig. 9. Variation of the oscillation frequency with capacitor C_2 with fixed I_{abc}=500μA.

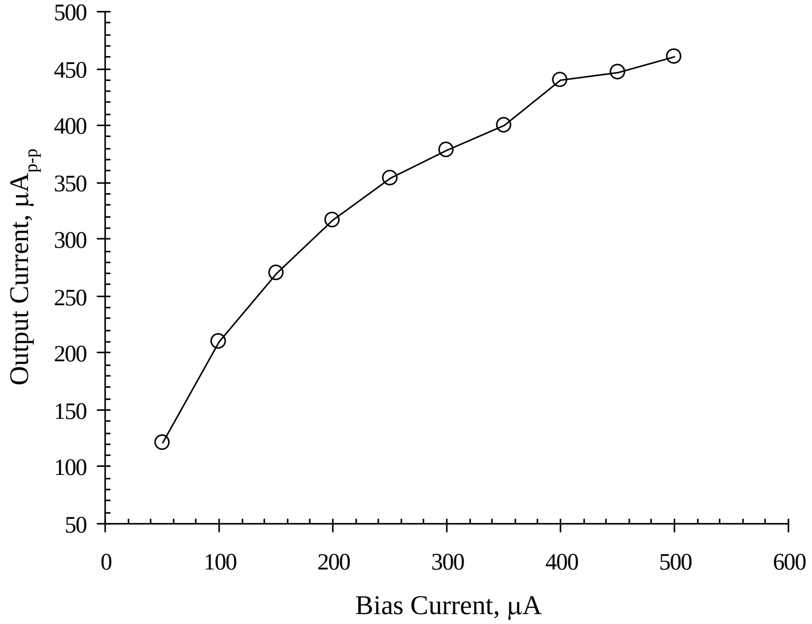

Fig. 10. Output current of proposed multiphase sinusoidal oscillator against varying bias currents with C_1=10pF and C_2=20.12pF.

Tables

Table 1. Condition and frequency of oscillation of multiphase sinusoidal oscillator.

Number of phase (*N*)	Condition of oscillation	Frequency of Oscillation (ω_o)
3	$C_2=2C_1$	$1.732g_m/C_2$
5	$C_2=1.237C_1$	$0.728g_m/C_2$
7	$C_2=1.11C_1$	$0.482g_m/C_2$
9	$C_2=1.063C_1$	$0.364g_m/C_2$

Table 2. Condition and frequency of oscillation of multiphase sinusoidal oscillator.

Number of phase (N)	Condition of oscillation	Frequency of Oscillation (ω_o)
3	$C_2=2C_1$	$1.732g_m/C_2$
4	$C_2=1.414C_1$	$1g_m/C_2$
5	$C_2=1.237C_1$	$0.728g_m/C_2$
6	$C_2=1.154C_1$	$0.577g_m/C_2$
7	$C_2=1.11C_1$	$0.482g_m/C_2$
8	$C_2=1.082C_1$	$0.414g_m/C_2$
9	$C_2=1.063C_1$	$0.364g_m/C_2$

Table 3. Model of the 0.5μm CMOS used in simulation.

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.MODEL NMOS LEVEL=3 PHI=0.700000 TOX=2.9900E-08 XJ=0.200000U TPG=1
VTO=0.6897 DELTA=0.0000E+00 LD=1.0250E-07 KP=7.7586E-05 UO=671.8
THETA=9.0430E-02 RSH=2.5430E+01 GAMMA=0.7618 NSUB=2.3320E+16
NFS=5.9080E+11 VMAX=2.0730E+05 ETA=1.1260E-01 KAPPA=3.1050E-01
CGDO=1.7757E-10 CGSO=1.7757E-10
CGBO=5.1336E-10 CJ=2.9018E-04 MJ=5.4207E-01 CJSW=1.3000E-10
MJSW=1.0000E-01 PB=9.8943E-01

.MODEL PMOS LEVEL=3 PHI=0.700000 TOX=2.9900E-08 XJ=0.200000U
TPG=-1 VTO=-0.7574 DELTA=2.9770E+00 LD=9.8570E-10 KP=2.2139E-05 UO=191.7
THETA=1.2020E-01 RSH=3.5220E+00 GAMMA=0.3992 NSUB=6.4040E+15
NFS=6.5000E+11 VMAX=2.6200E+05 ETA=1.4820E-01 KAPPA=1.0000E+01
CGDO=5.0000E-11 CGSO=5.0000E-11
CGBO=4.2738E-10 CJ=2.9788E-04 MJ=4.1852E-01 CJSW=1.6452E-10
MJSW=1.1224E-01 PB=7.4167E-01
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Table 4. The MOS transistors aspect ratios.

MOS Transistors	W/L (μm/μm)
M1,M2	20/2
M3,M4,M5,M6,M9,M10,M13,M14,M17,M18	40/2
M7,M8,M11,M12,M15,M16,M19,M20	46/2