Electronically Tunable Current-mode Multiphase Sinusoidal Oscillator Employing CCCDTA-based Allpass Filters with Only Grounded Passive Elements

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Abstract. *This study describes the design of a multiphase sinusoidal oscillator (MSO) using CCCDTA-based allpass filters with grounded capacitors. The oscillation condition and oscillation frequency can be electronically/orthogonally controlled. The proposed MSO provides 2n (n ≥ 2) phase signals that are equally spaced in phase and equal amplitude. The circuit requires one CCCDTA, one electronic resistor and one grounded capacitor per phase and no additional current amplifier and floating elements. High output impedances of the configuration enable the circuit to be cascaded to the current-mode circuit without additional current buffers. The effects of the non-idealities of the CCCDTA-allpass sections were also studied. The results of PSPICE simulations using CMOS CCCDTA are presented, demonstrating their consistency with theoretical assumptions.*

Keywords

Multiphase sinusoidal oscillator, CCCDTA, current-mode.

1. Introduction

Multiphase sinusoidal oscillator (MSO) is important blocks for various applications. For example, in telecommunications it is used for phase modulators, quadrature mixers [1], and single-sideband generators [2]. In measurement system, MSO is employed for vector generator or selective voltmeters [3]. It can also be utilized in power electronics systems [4]. Recently, current-mode circuits have been receiving considerable attention of due to their potential advantages such as inherently wide bandwidth, lower slew-rate, greater linearity, wider dynamic range, simple circuitry and low power consumption [5]. Many active building blocks (ABBs) have been proposed to realize the current-mode circuit, for example operational amplifier (OTA), second generation current conveyor (CCII), second generation current-controlled current conveyor (CCCII), current-feedback amplifier (CFA), current differencing buffered amplifier (CDBA), etc. The interesting active element, called current differencing transconductance amplifier (CDTA), is introduced to provide new possibilities in the current-mode circuit. The CDTA seems to be a versatile component in the realization of a class of analog signal processing circuit; especially analog frequency filters [6]. It is really current-mode element whose input and output signals are currents. In addition, output current of CDTA can be electronically adjusted. Besides, the modified version of CDTA wherein the intrinsic resistances at two current input ports can be electronically controlled has been proposed in [7]. This CDTA is called current controlled current differencing transconductance amplifier (CCCDTA).

Several realizations of current-mode MSOs using different active building blocks are available in the literature. These include realizations using current follower (CF) [8], CCCII [9]-[10], and most recently by CDTA [11]-[13]. The CF-based MSO in [8] requires two current followers, one floating resistor, and one floating capacitor for each phase and thus the circuit is not suitable for monolithic integration. Moreover, it cannot be electronically controlled. The CCCII-based MSOs [9]-[10] enjoy high-output impedances and electronic tunability. However, the first one requires a large number of external capacitors. In addition, the oscillation condition can be provided by tuning the capacitance ratio of external capacitors, which is not easy to implement. The second reported circuit requires additional current amplifiers, which makes the circuit more complicated and increases its power consumption. CDTA-based current-mode MSOs in [11] is based on lossy integrators, whereas the circuits in [12] and [13] contain CDTA-based allpass sections. They exhibit good performance in terms of electronic tunability, high-output impedances, and independent control of the oscillation frequency and the oscillation condition. However, MSOs in [11] and [12] require an additional current amplifier, which is implemented by two CDTAs. Moreover, the output currents of the MSO, utilizing the CDTA-based lossy integrators, are of different amplitudes. The MSO employing CDTA-based allpass sections [12] requires two CDTAs in each allpass section, and the circuitry becomes more extensive. While MSO using CDTA-based allpass sections [13] requires floating capacitor. Consequently, it occupies a larger chip area for VLSI design. In addition, its power consumption is also increased. Other voltage-mode MSOs have been presented in the literature [14-24]. The proposed MSOs are compared with previously published MSOs of [9-23] and the results are shown in Tab. 1.

Ref	**Design technique**	**Active element**	**No. of active element per phase**	**Additional amplifier**	**Grounded C only**	**No. of R+C per phase**	**Electronic control**	**CM output**
[9]	Losy integrator	CCCII	1	No	Yes	0+2	Yes	Yes
[10]	Losy integrator	CCCII	1	Yes	Yes	1+1	Yes	Yes
[11]	Losy integrator	CDTA	1	Yes	Yes	0+1	Yes	Yes
[12]	Allpass filter	CDTA	2	Yes	No	0+1	Yes	Yes
[13]	Allpass filter	CDTA	1	No	No	2+1	Yes	Yes
[14]	Allpass filter	Opamp	1	Yes	Yes	3+1	No	No
[15]	Losy integrator	Opamp	1	No	No	2+1	No	No
[16]	Losy integrator	OTA	1 (Fig. 2a)	No	Yes	1+1	Yes	No
		OTA & Buffer	1 OTA, 1 Buffer (Fig. 2b)	No	Yes	2+1	Yes	No
		OTA	2 (Fig. 3a)	No	Yes	0+1	Yes	No
		OTA & Buffer	1 OTA, 1 Buffer (Fig. 3b)	No	No	0+3	Yes	No
[17]	Losy integrator	OTA	1	Yes	Yes	0+1	Yes	No
[18]	Losy integrator	CFOA	1	No	*	2+0	No	No
[19]	Losy integrator	CCII	1	No	Yes	2+1	No	No
[20]	Losy integrator	OTA & Buffer	1 OTA, 1 Buffer	No	Yes	2+1	No	No
[21]	Losy integrator	CCII	1	No	*	3+0	No	No
[22]	Losy integrator	CCII	1	Yes	Yes	2+1	No	No
[23]	Losy integrator	CDBA	1	Yes	Yes	2+1	No	No
Proposed MSOs	Allpass filter	CCCDTA	1	No	Yes	1+1	Yes	Yes

* No use of external capacitor

Tab. 1. Comparison between various MSOs.

This paper presents a new MSO realization based on allpass filter with the following features:

- Use of grounded capacitors and identical circuit configuration for each section in the MSO topology which are suitable for integration.
- The electronic tunability of oscillation condition and oscillation frequency.
- High-impedance current outputs.
- The possibility of generating multi-phase signals for both an even and an odd number of equally-spaced in phases.
- Independent tuning of the oscillation frequency and the oscillation condition.
- Equality of amplitudes of each phase due to utilizing identical sections.
- Requirement for only one CCCDTA as the active element for each phase without any additional current amplifiers and floating elements.

2. Theory and Principle

2.1 Basic Concept of CCCDTA

The principle of the CCCDTA was published in 2006 by W. Jaikla and S. Siripruchyanun [7]. It was modified from the first generation CDTA [6]. The schematic symbol and the ideal behavioral model of the CCCDTA are shown in Fig. 1(a) and (b). It has finite input resistances: R_p and R_n at the p and n input ports, respectively. These intrinsic resistances are equal and can be controlled by the bias current I_{B1}. The difference of the i_p and i_n input currents flows from port z. The voltage v_z on z terminal is transferred into current using transconductance g_m, which flows into output terminal x. The g_m is tuned by I_{B2}. In general, CCCDTA can contain an arbitrary number of x terminals, providing currents I_x of both directions. The characteristics of the ideal CCCDTA are represented by the following hybrid matrix:

$$\begin{bmatrix} V_p \\ V_n \\ I_z \\ I_x \end{bmatrix} = \begin{bmatrix} R_p & 0 & 0 & 0 \\ 0 & R_n & 0 & 0 \\ 1 & -1 & 0 & 0 \\ 0 & 0 & 0 & \pm g_m \end{bmatrix} \begin{bmatrix} I_p \\ I_n \\ V_x \\ V_z \end{bmatrix}. \tag{1}$$

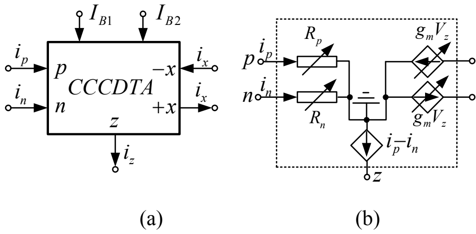
If the CCCDTA is realized using CMOS technology, R_p, R_n and g_m can be respectively written as

$$R_p = R_n = \sqrt{\frac{1}{k_R I_{B1}}}; k_R = 8\mu_n C_{ox}\left(\frac{W}{L}\right)_{8-11} = 8\mu_n C_{ox}\left(\frac{W}{L}\right)_{12-15}. \tag{2}$$

and

$$g_m = \sqrt{k_g I_{B2}}; k_g = \mu_n C_{ox}\left(\frac{W}{L}\right)_{29,30}. \tag{3}$$

Here k is the physical transconductance parameter of the MOS transistor. The CMOS implementation of the CCCDTA is shown in Fig. 2.



(a) (b)

Fig. 1. CCCDTA (a) Symbol. (b) Equivalent circuit.

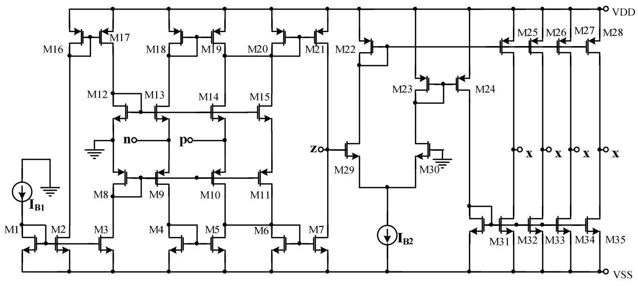


Fig. 2. Schematic of the CMOS CCCDTA.

2.2 Principle of n-cascaded Allpass-based Multiphase Sinusoidal Oscillator

The generalized structure of MSO by cascading the n identical stages ($n \geq 2$) is shown in Fig. 3 containing the first-order allpass filter for each phase. The output of nth stage is fed back to the input of the first stage, and the signal of the last section is inverted for even phase system and non-inverted for odd phase system. It is found in Fig. 3 that the system can provide one phase per one allpass filter without any additional external amplifier. The system loop gain can be written as follows [14]:

$$L(s) = K_1 K_2 .. K_n \left(\frac{s-a}{s+a}\right)^n \tag{4}$$

where the symbols K_i is the current gain and a denotes the natural frequency of each allpass section. The odd and even numbers of n are cooperated with positive and negative signs of K, respectively. At the oscillation frequency $\omega_{osc} = 2\pi f_{osc}$, the Barkhausen's condition can be written as

$$L(j\omega_{osc}) = \left(K\frac{j\omega_{osc} - a}{j\omega_{osc} + a}\right)^n = 1 \tag{5}$$

where $K_1 = K_2 = \ldots = K_n = K$, then $K_1 K_2 \ldots K_n = K^n$. From (5), the magnitude and the phase of the system loop gain can be expressed as follows:

$$|L(j\omega_{osc})| = 1, \tag{6}$$

and

$$\angle H(j\omega_{osc}) = 2n\phi = 2n\left(-2\tan^{-1}\left(\frac{\omega_{osc}}{a}\right)\right) = -2\pi. \tag{7}$$

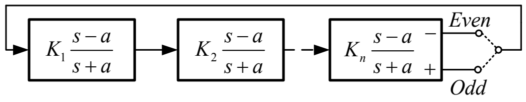


Fig. 3. MSO based on n-cascaded first order allpass filter.

Equation (7) shows that for n - phase systems, each phase is shifted by -360°/2n. Hence the oscillation condition (OC) and the oscillation frequency (OF) are given by the formulae

$$\text{OC: } K = \sqrt{\frac{(\omega_{osc}/a)^2 + (1)^2}{(\omega_{osc}/a)^2 + (-1)^2}} = 1, \tag{8}$$

and

$$\text{OF: } \omega_{osc} = a\tan(\pi/2n). \tag{9}$$

Considering (8) and (9), the oscillation condition can be controlled independently of the oscillation frequency by the gain K, while the oscillation frequency can be changed by the natural frequency a.

2.3 Proposed Current-mode Multiphase Sinusoidal Oscillator

As mentioned in the above section, the proposed MSO is based on identical first-order allpass sections. A prospective CCCDTA-based implementation is shown in Fig. 4. It is seen that the proposed first-order allpass circuit consists of 1 CCCDTA, 1 grounded capacitor and electronic resistor (R_k) which is easy to fabricate, unlike the previous all-pass circuits that used floating passive elements [25] or excessively used a large number of passive and active elements [26]. The transresistance of the electronic resistor circuit can be expressed as [27].

$$R_K = \frac{V_{in}}{I_{in}} = \frac{L}{2\mu C_{OX} W \left(V_{DD} - V_T\right)} \qquad (10)$$

where V_T denotes the threshold voltage. Note that the output currents of the filter are available in both directions (positive and negative). The current transfer function can be written as follows:

$$\frac{I_O(s)}{I_{in}(s)} = g_m R_K \left(\frac{s - \frac{1}{R_n C}}{s + \frac{1}{R_n C}} \right). \qquad (11)$$

According to (8) and (9), the oscillation condition and oscillation frequency are as follows:

$$\text{OC: } g_m R_{Ki} = 1,\ i = 1, 2, .., n,. \qquad (12)$$

and

$$\text{OF: } \omega_{osc} = \frac{1}{R_n C} \tan\left(\frac{\pi}{2n}\right). \qquad (13)$$

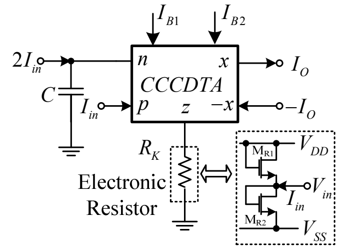


Fig. 4. CCCDTA-based allpass filter with grounded capacitor.

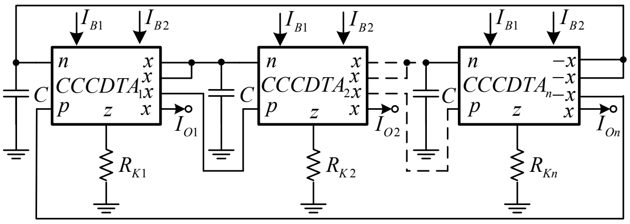


Fig. 5. Proposed current-mode MSO for even phase system.

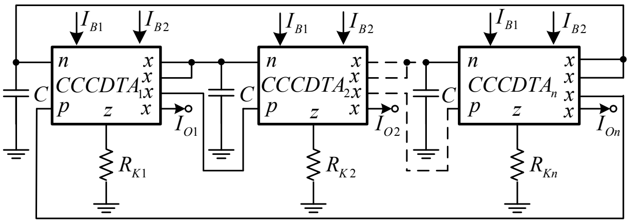


Fig. 6. Proposed current-mode MSO for odd phase system.

Substituting $R_n = 1/\sqrt{k_R I_{B1}}$ and $g_m = \sqrt{k_g I_{B2}}$ into (12) and (13), the oscillation condition and oscillation frequency become

$$\text{OC: } R_{Ki}\sqrt{k_g I_{B2}} = 1,\ i = 1, 2, .., n, \qquad (14)$$

and

$$\text{OF: } \omega_{osc} = \frac{\sqrt{k_R I_{B1}}}{C} \tan\left(\frac{\pi}{2n}\right). \qquad (15)$$

From (14) and (15), it can be seen that the OC can be adjusted electronically/independently from the OF by varying I_{B2} while the oscillation frequency can be electronically adjusted by I_{B1}. The resulting current-mode MSOs are shown in Fig. 5 and Fig. 6 for even and odd phase system, respectively. It is found from Figs. 5 and 6 that the current mirrors are required to split the bias currents I_{B1} and I_{B2} to each allpass section.

3. Non-ideal Case

For a complete analysis of the circuit, it is necessary to take into account the following two parts of CCCDTA non-idealities.

3.1 Differential Current Gain at z-Terminal

$$I_z = \alpha_p i_p - \alpha_n i_n \qquad (16)$$

where α_p and α_n are the current transfer gains from p and n to z terminals, respectively. All these gains slightly differ from their ideal values of unity by current tracking errors of n and p input ports (ε_n and ε_p) as $\alpha_n \approx 1 - \varepsilon_n$ and $\alpha_p \approx 1 - \varepsilon_p$. Considering the current transfer gains, the modified current transfer function of Fig. 4 can be expressed as

$$\frac{I_O(s)}{I_{in}(s)} = \frac{g_m R_K \left(s - \frac{2 - \alpha_p/\alpha_n}{R_n C} \right)}{s + \frac{1}{R_n C}}. \qquad (17)$$

In this case, re-analyze the proposed MSO circuit for $n = 3$, the oscillation condition and oscillation frequency are modified as

OC:

$$\frac{9\left[1+\left(\left(g_m R_k\right)^3\left(2-\alpha_p/\alpha_n\right)\right)\right]\left[1-\left(\left(g_m R_k\right)^3\left(2-\alpha_p/\alpha_n\right)^2\right)\right]=}{\left[1-\left(g_m R_k\right)^3\right]\left[\left(1+\left(\left(g_m R_k\right)^3\left(2-\alpha_p/\alpha_n\right)^3\right)\right)\right]}, \qquad (18)$$

and

$$\text{OF: } \omega_{0n} = \sqrt{\frac{1}{3}\left(\frac{1+\left[\left(g_m R_k\right)^3\left(2-\alpha_p/\alpha_n\right)^2\right]}{1+\left[\left(g_m R_k\right)^3\left(2-\alpha_p/\alpha_n\right)\right](RC)^2}\right)}. \qquad (19)$$

By the structure of CCCDTA in Fig. 2, the current gains (α_p and α_n) are normally identical and very close to unity in the operation frequency range. The current tracking error (ε_p and ε_n) of p and n terminals generated by the current mirrors (M_4-M_5, M_6-M_7, M_{18}-M_{19} and M_{20}-M_{21}) can be reduced by replacing the cascode or wilson current mirrors [5] instead. From (18) and (19), it is clear that if $g_m = 1/R_K$, the current tracking errors provide small affecting the oscillation condition and oscillation frequency.

3.2 The Parasitic Elements at Several Ports

The parasitic resistances and capacitances appear between the high-impedance z and x terminals of the CCCDTA as shown in Fig. 7. If $R_K << R_Z$ and $C_x << C$, the current transfer function of the allpass filter is approximated

$$\frac{I_O(s)}{I_{in}(s)} \approx \frac{g_m R_K\left(s\dfrac{CR_n}{CR_n + R_K C_z} - \dfrac{1}{CR_n + R_K C_z}\right)}{s + \dfrac{1}{CR_n + R_K C_z}}. \tag{20}$$

For the specific case, the parasitic effects on allpass circuit can be avoided by choosing $CR_n >> C_zR_K$.

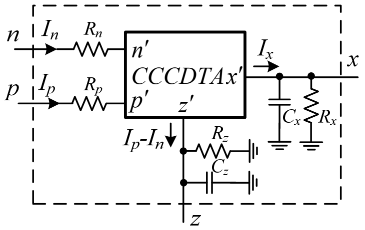


Fig. 7. Proposed current-mode MSO for odd phase system.

4. Simulation Results

The proposed MSO has been simulated in PSpice using the CMOS implementation of the CCCDTA as shown in Fig. 2. The PMOS and NMOS transistors have been simulated by respectively using the parameters of a 0.25µm TSMC CMOS technology [28] with ±1.5V voltage supply. The aspect ratios of PMOS and NMOS transistor are listed in Tab. 2. As an example, the three-phase sinusoidal oscillator based on the structure in Fig. 3 has been designed on the basis of Fig. 6. The bias currents were set as follows: I_{B1} = 50 µA, I_{B2} = 104 µA. To avoid the parasitic effects, the capacitors C = 100 pF are selected. The simulated output waveforms, I_{O1}, I_{O2} and I_{O3} around 1 MHz are shown in Fig. 8. The frequency spectrum of output current is shown in Fig. 9. The total harmonic distortion at 1 MHz is less than 1%. The tuning of the FO versus the bias current I_{B1} with different capacitor values is shown in Fig. 10. It proves that the simulation results are in a good accordance with the theoretical formula (15).

Transistor	W (µm)	L (µm)
M1-M7	5	0.5
M8-M11	4	0.5
M12-M15	2	0.5
M16-M18, M20-M21	15	0.5
M19	14.5	0.5
M22-M23, M25-M28	5	0.25
M24	4.2	0.25
M29-M30	25	0.25
M31-M35	3	0.25
MR1-MR2	3.8	0.5

Tab. 2. Dimensions of the transistors.

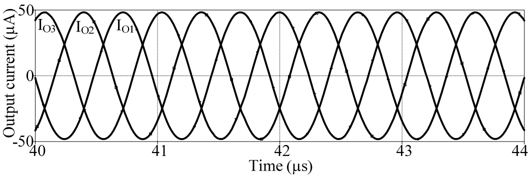


Fig. 8. Current outputs of the proposed MSO (n = 3).

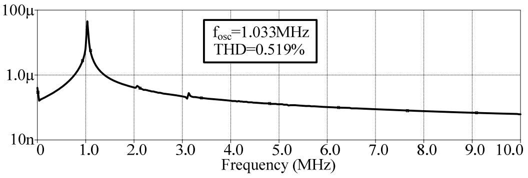


Fig. 9. Spectrum of signal in Fig.8.

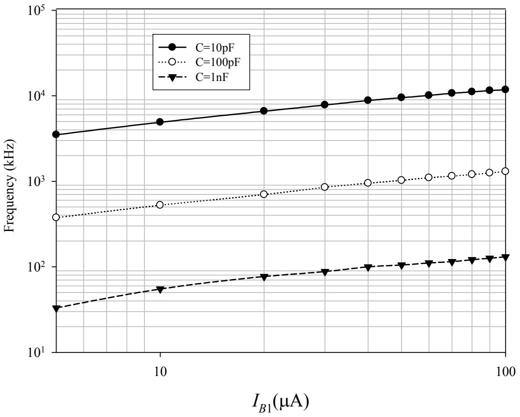


Fig. 10. Simulated oscillation frequency versus I_{B1} for different capacitances C.

5. Conclusion

A new current-mode multiphase sinusoidal oscillator using CCCDTA-based allpass filters with grounded capacitors has been presented. The features of the proposed circuit are that: oscillation frequency and oscillation condition can be independently tuned; the proposed oscillator consists of merely 1 CCCDTA, 1 electronic resistor and 1 grounded capacitor for each phase and no additional current amplifier, non-interactive dual-control of both the CO and FO and availability of explicit-current outputs from high-output impedance terminals. PSPICE simulation results agree well with the theoretical anticipation.

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