Four-Phase Oscillators Employing Two Active Elements

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Abstract. *Two novel four-phase voltage-output oscillators are proposed. These circuits can also be utilized as quadrature oscillators with floating outputs. Each oscillator employs two DO-CIBA (Differential Output- Current Inverter Buffered Amplifier), two grounded capacitors, and four or three resistors. Independent control of the oscillation frequency (OF) and oscillation condition is practicable in both oscillators. Real measurements on the oscillator specimens confirm the ability of easy OF control and extra low THD, which is less than 0.07%.*

Keywords

Four-phase oscillator, DO-CIBA.

1. Introduction

Four-phase oscillators are a special case of multi-phase sinusoidal oscillators (MSO), the latter generating n independent harmonic signals with constant phase shifts $\Delta\varphi = 360°/n$. Their applications are used in many areas of electrical engineering, signal processing, and measurement [1]. On the other hand, the four-phase oscillator can be regarded as a generalized quadrature oscillator with both quadrature signals and their inverted counterparts being available. Under certain conditions, the four-phase oscillator can be used as a floating-output quadrature oscillator.

Many types of the multi-phase oscillators which employ various active elements are described in the literature. Let us mention particularly the conventional operational amplifiers [2], [3], CFOAs (Current Feedback Operational Amplifiers) [4], OTA (Operational Transconductance Amplifier) [5], CCII (Current Conveyor of the 2nd Generation) [6]-[9], CDBA (Current Differencing Buffered Amplifier) [10], and CDTA (Current Differencing Transconductance Amplifier) [11]-[13]. Some of papers deal with quadrature oscillators [14]-[41] with single-ended voltage outputs or single current outputs. So far no publication of four-phase oscillators has been found in literature which fulfils simultaneously the following conditions:

1) Four low-impedance outputs without the necessity of their additional buffering, with the possibility of utilizing them as two floating sources of quadrature signals.
2) Employing maximally two simple active elements and only grounded capacitors.
3) The possibility of tuning the oscillation frequency (OF) without violating the oscillation condition (OC), and automatically setting the OC without disturbing the OF.
4) Equal amplitudes of all generated signals.
5) Fulfilling condition 4) also while tuning the OF.

Two oscillators are described in this paper. The first one fulfils all five conditions, the second one the first four. Special active elements with a simple internal structure, namely DO-CIBA (Differential Output- Current Inverter Buffered Amplifier) with differential voltage outputs are used. These elements are briefly described in the following Section. Section 3 contains a description of the oscillator proposed, and the theoretical formulae for OF and OC are analyzed there. An error analysis of real influences is described in Section 4. The experimental results of Section 5 show a good agreement with the theoretical assumptions.

2. DO-CIBA

The schematic symbol and behavioral model of the DO-CIBA are shown in Fig. 1 (a) and (b), respectively. Unlike the conventional CDBA, the input current differential unit (CDU) [42] is replaced here by a simpler current inverter, and the output voltage buffer is supplied by the differential output.

The DO-CIBA equations follow from Fig. 1:

$$\begin{vmatrix} I_z \\ V_w \\ V_{\overline{w}} \\ V_n \end{vmatrix} = \begin{vmatrix} 0 & 0 & 0 & -1 \\ 1 & 0 & 0 & 0 \\ -1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \end{vmatrix} \begin{vmatrix} V_z \\ I_w \\ I_{\overline{w}} \\ I_n \end{vmatrix} \tag{1}$$

The I_n current flowing to the low-impedance input n is inverted in the CI (Current Inverter) block, and it flows out of the high-impedance z terminal to the external circuit.

The corresponding voltage drop is buffered to the differential output as voltages V_w and $V_{\overline{w}} = -V_w$.

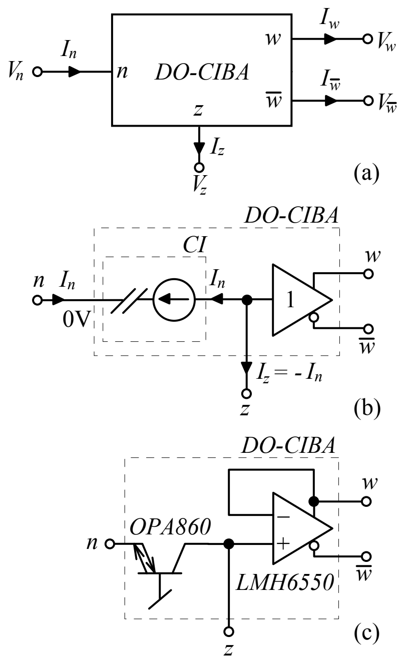

Fig. 1. DO-CIBA: (a) schematic symbol, (b) behavioral model, (c) example of DO-CIBA implementation from commercial integrated circuits.

Since the output voltage is of both polarities, the negative as well as the positive feedback can be simply accomplished via external circuits, regardless of the fact that the current input of this element is only inverting (I_n).

For fast experimental verification of applications of the DO-CIBA element, its implementation from inexpensive off-the-shelf components can be used. As shown in Fig. 1 (c), the current inverter can be implemented by means of the so-called diamond transistor OPA860 [43], which is a positive current conveyor of the 2nd generation with the resistance of the x terminal (emitter) ca 10 Ω [43]. A fast differential-output voltage buffer can be made, for example, via the fully differential OpAmp LMH6550 [44]. This layout was used within the experiments described in Section 5.

The DO-CIBA is used in this paper for the synthesis of oscillators generating either single-ended four-phase signals or two differential quadrature signals. With one of the orthogonal pairs omitted, the circuits can be used as conventional single-ended quadrature oscillators. The first circuit employs two DO-CIBAs, two grounded capacitors, and four resistors. This topology provides several degrees of freedom for independent OF and OC control. A small re-arrangement of this circuit yields a simplification to the canonic structure which utilizes only three resistors, at the cost of decreasing the above degrees of freedom. The independent OF and OC control is still practicable but the dynamic range of the OF control is decreased. Both oscillators are made up of integrated circuits as shown in Fig. 1 (c), and their functionality is experimentally verified with the conclusion that the behavior of the tested circuits corresponds to the theory and to the analysis of real influences.

3. Proposed Oscillators

The core of the oscillator in Fig. 2 (a) is a pair of integrators within a feedback loop. Integrator No. i consists of active element No. i and a pair of R_i, C_i, i = 1, 2. Also, both positive and negative feedbacks via resistors R_3 and R_4 are implemented in integrator No. 1. The oscillation condition is fulfilled when the feedback actions are in equilibrium. Based on this simple consideration, the formulae in Table 1 for the OF and also for the OC (ω_0) can be derived since the latter frequency is determined by the time constants of both integrators. The inequality in the OC formula designates the predominance of the positive feedback and thus a state of increasing oscillations.

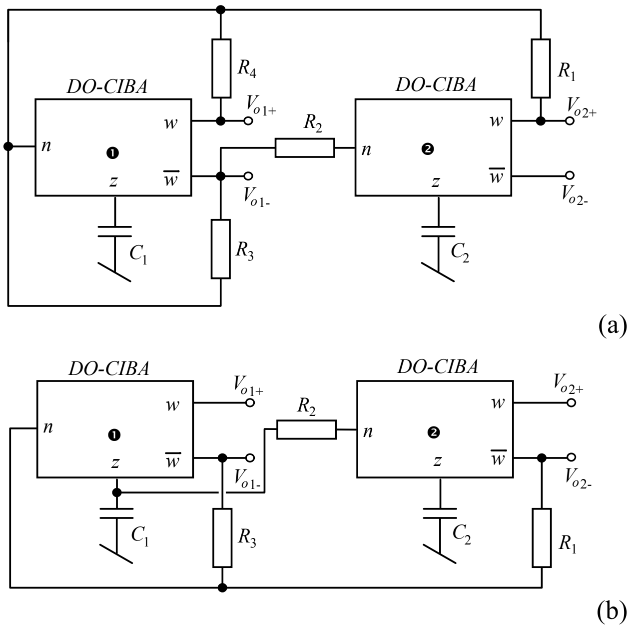

Fig. 2. Two versions (a) and (b) of the proposed oscillators.

circuit version→	(a)	(b)
OF	$\dfrac{1}{\sqrt{R_1 R_2 C_1 C_2}}$	
OC	$\dfrac{R_3}{R_4} \le 1$	$\dfrac{R_3}{R_2} \le 1$
OF indep. control by	R_1, R_2, C_1, C_2	R_1, C_1, C_2
OC indep. control by	R_3, R_4	R_3
V_{o2}/V_{o1}	$j\sqrt{\dfrac{R_1}{R_2}\dfrac{C_1}{C_2}}$	

Tab. 1. Comparison of the parameters of oscillators from Fig. 2 (a)-(b).

An analysis of OF and OC reveals that the oscillation frequency can be set independently of OC via R_1, R_2, C_1, C_2 while the oscillation condition can be adjusted by means of R_3 and R_4 without violating OF.

Considering that the signals denoted V_{o2+} and V_{o1+} in Fig. 2 (a) are output and input voltages of integrator No. 2, their ratio will be as follows:

$$\frac{V_{o2}}{V_{o1}} = \frac{1}{j\omega R_2 C_2}. \quad (2)$$

Substituting the formula for OF from Tab. 1 into this equation, the voltage ratio will be as shown in the last row of Tab. 1. It confirms the fact that the signals V_{o1+} and V_{o2+} are in the quadrature, and that the circuit in Fig. 2 (a) represents a four-phase oscillator with equally spaced phase shifts. Fulfilling the equality $R_1 = R_2 = R$, the oscillation frequency can be modified through R without modifying the ratios of the amplitudes of the signal generated, and also without disturbing the oscillation condition.

The oscillator in Fig. 2 (a) contains four resistors and thus it is not in the canonic structure. The modification to the canonic form is shown in Fig. 2 (b). The damping of integrator No. 1, accomplished in Fig. 2 (a) by a resistor R_4, i.e. via negative feedback, is now implemented by resistor R_2, which is connected between capacitor C_1 and low-impedance input n of CIBA No. 2. R_2 serves also to excite CIBA No. 2 from the output of the first integrator. It is a function similar to that performed by R_2 in structure (a) but R_2 is now connected to the non-inverting output voltage of the CIBA. That is why the global feedback via R_1 in circuit (b) must lead from the inverting output of integrator No. 2. As a result, such an accumulation of two operations in a single element saves one resistor. A more detailed analysis yields the results from Tab. 1: The OF is the same as for circuit (a) because this frequency is still given by the time constants of both integrators. Now R_2 appears in the OC instead of R_4. The OF can be controlled by means of R_1, C_1, or C_2 without disturbing the OC while the OC can be set without modifying the OF only via R_3. Furthermore, R_1 can control the OF within a smaller range than via a simultaneous modification of R_1=R_2 for circuit (a), and such OF control will be also accompanied by a modification of the ratio of magnitudes of the signals generated. In this sense, circuit (b) is an economical version of circuit (a) with a worse performance when the oscillation frequency must be modified.

4. Analysis of Real Influences

As follows from the experimental Section 5, the oscillator specimens have shown the proposed performance but with certain differences between the theoretical and real values of the oscillation frequency. The symbolic analysis of both circuits in Fig. 2 revealed the dominant real parameters of active elements which are responsible for these differences: parasitic resistance and capacitance R_z and C_z of the z terminal, resistance R_n of the n terminal, and current gain $\alpha = I_z/I_n$ of the current inverter, which can be deflected from its ideal value 1. Equations for OF and OC were again derived but this time with the above factors taken into consideration. The real parameters were indexed by numbers 1 or 2 depending on whether they describe the parameters of DO-CIBA No. 1 or 2 in Fig. 2. The final formulae are given in Tab. 2 in the columns OF (oscillation frequency), OC (oscillation condition) and OF+OC (oscillation frequency on the assumption of fulfilling the oscillation condition). Note that the simpler formulae in the OF+OC column can be advantageously used for oscillators which are provided with circuits for automatic stabilization of the amplitude of generated waveforms. Various trends in influencing the OF by parasitic parameters are evident from the data in column OF: decreasing the oscillation frequency via the parasitic resistance of the n terminal of DO-CIBA No. 2 and via the capacitances of the z terminals of both active elements, OF increase/decrease with increasing/decreasing current gains α above/below their ideal values 1, and the influence described by the last term in the formula where the effect depends on the mutual configuration of real parameters. However, the results in the OF+OC column clearly show that the frequency is always less than its theoretical value when the OC is fulfilled and when the α gains are not greater than 1. In order to minimize this decrease, three influences should be eliminated: parasitic n terminal resistance of the second DO-CIBA (i.e. designing $R_2 >> R_{n2}$), parasitic capacitances of both z terminals (i.e. $C_1 >> C_{z1}$ and $C_2 >> C_{z2}$), and parasitic z terminal resistance of CIBA No. 2 (i.e. maximizing the time constant $R_{z2}C_2$).

It is obvious from the column OC that, in contrast to the theoretical case, R_3 must be a little smaller than R_4 in order to maintain the steady-state oscillations in the circuit in Fig. 2 (a). For the second oscillator, the state is less clear since the result can be influenced by the non-ideal current gain of the current inverter of active element No. 1.

5. Experimental Verification

Both versions of the oscillator in Fig. 2 were manufactured from discrete components, whereas the DO-CIBA elements were implemented as shown in Fig. 1 (c). According to [43], the transconductance of OPA860 was set to ca 100 mS via an external resistor with R_{set} = 330 Ω. The corresponding resistance of the n terminal is ca 10 Ω. The capacitances used in the circuits were designed as follows: $C_1 = C_2$ = 82 pF. Resistor R_3 was implemented via a photoresistor which is a part of the 3WK16341 optron [45] for amplitude stabilization. The internal LED was driven by a current which was derived from the generated signal V_{o1+}. The oscillation frequency was controlled by a parallel variation of resistances $R_1 = R_2$ for oscillator (a) and by R_1 with a fixed value of R_2 = 1.8 kΩ for oscillator (b). A demonstration of steady-state waveforms for the oscillator (a) is given in Fig. 3.

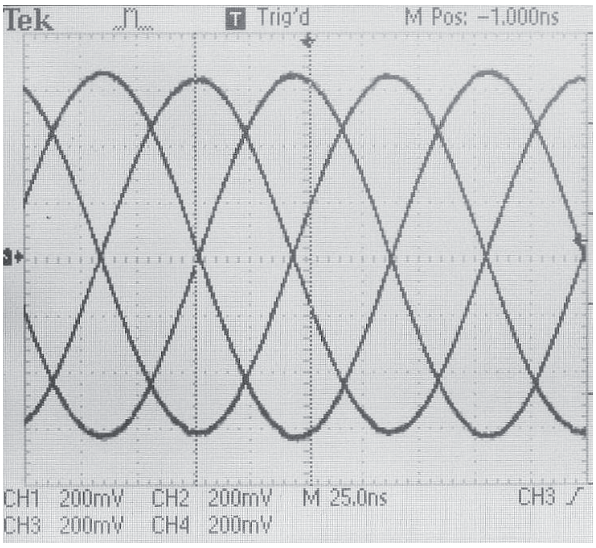

Fig. 3. Oscillogram of four generated signals V_{o1+}, V_{o1-}, V_{o2+}, V_{o2-} for the oscillator from Fig. 2 (a).

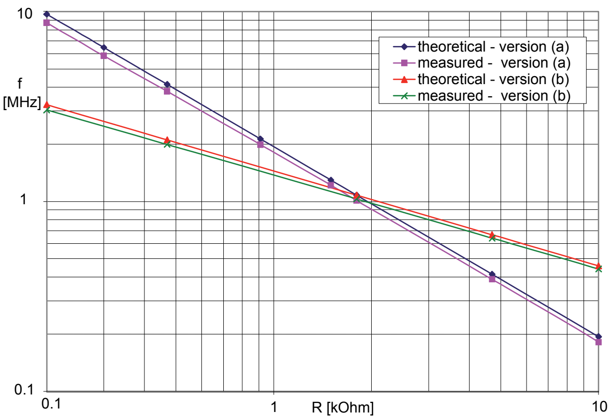

Fig. 4. Oscillation frequency versus resistances $R = R_1 = R_2$ (circuit (a)) and $R = R_1$ (circuit (b)).

Fig. 4 illustrates the OF control via the above specified resistors. It is evident that the frequencies measured are decreased below the theoretical values by a systematic error which can be understood from the formulae in the OF+OC column in Tab. 2. This error is approximately 5 % when considering only the influence of parasitic resistance $R_n = 10\ \Omega$. Taking into account also the other real parameters, i.e. C_1 and C_2 increase by ca 3 pF (2 pF parasitic capacitance of the collector of the diamond transistor plus 1 pF input capacitance of the buffer), 54 kΩ z-terminal parasitic resistance (collector resistance of the diamond transistor), and real current gains $\alpha \approx 0.97$, then the values measured correspond well to those from the formulae in Tab. 2, column OF+OC. It confirms that the error analysis from Section 4 describes the dominant real influences.

Owing to the circuit for automatic amplitude stabilization, the signals generated have a low harmonic distortion. For amplitude of 3V and a frequency of 1 MHz, the THD measured was below 0.07 percent.

6. Conclusion

It is shown in the paper that the active element CIBA with differential voltage output is useful for implementing the multi-phase sinusoidal oscillators. The reasons are as follows:

- In comparison with CDBA, DO-CIBA has a simple internal structure because it contains a current inverter instead of the more complicated current differencing unit. The differential output is implemented in a standard way known from the differential OpAmps.
- The differential voltage output together with the input inverter enables an easy realization of inverting and non-inverting integrators. This is important for the parallel implementation of the local positive and negative feedbacks round the active element No. 1 in the oscillator topology, where the oscillation condition is fulfilled without disturbing OF just when the effects of both feedbacks are compensated. The oscillation frequency is given by the gain of the global feedback loop led through both integrators.
- Differential output of DO-CIBA facilitates the utilization of the generated signals as floating signals with twofold peak-to-peak value in comparison with the single-ended signals of individual phases.

Measurements on the oscillator specimens confirmed the proposed parameters including the frequency control via resistors and an extra low harmonic distortion of generated signals.

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	OF ω_0^2	OC	OF+OC ω_0^2
(a)	$\frac{\alpha_1\alpha_2}{R_1R_2'C_1'C_2'}+\frac{\alpha_1(G_4-G_3)+G_{z1}}{R_{z2}C_1'C_2'}$	$\frac{R_3}{R_4}\le 1-\frac{C_1'}{\alpha_1 C_2'}\frac{R_3}{R_{z2}}-\frac{R_3}{\alpha_1 R_{z1}}$	$\frac{\alpha_1\alpha_2}{R_1R_2'C_1'C_2'}-\frac{1}{R_{z2}^2C_2'^2}$
(b)	$\frac{\alpha_1\alpha_2}{R_1R_2'C_1'C_2'}+\frac{G_{z1}+G_2'-\alpha_1 G_3}{R_{z2}C_1'C_2'}$	$\frac{R_3}{R_2'}\le \alpha_1-\frac{C_1'}{C_2'}\frac{R_3}{R_{z2}}-\frac{R_3}{R_{z1}}$	$\frac{\alpha_1\alpha_2}{R_1R_2'C_1'C_2'}-\frac{1}{R_{z2}^2C_2'^2}$
	$R_2' = R_2 + R_{n2}$, $C_1' = C_1 + C_{z1}$, $C_2' = C_2 + C_{z2}$		

Tab. 2. OF and OC of the oscillators from Fig. 2 (a), (b) with real influences taken into consideration.

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