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Novel Third–Order Quadrature Oscillators with Grounded Capacitors

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Original scientific paper

This paper presents two Current Differencing Transconductance Amplifiers (CDTA)–based current–mode resistors–less variable frequency third–order Quadrature Oscillators (TOQO). The proposed TOQOs consist of minimum number of active and passive components, especially the first TOQO, only two CDTAs and three capacitors are used in it. The two TOQOs are completely resistor–less, and the capacitors used in the TOQOs are all grounded, which are ideal for monolithic integration. The condition of oscillation (CO) and frequency of oscillation (FO) of the TOQOs can be controlled electronically and independently, which make them suitable for variable frequency oscillator (VFO). Moreover, the two TOQOs can provide four explicit quadrature current outputs at high output impedance terminals, and they can be directly cascaded with other current–mode circuits without any impedance matching requirements. Cadence IC Design Tools 5.1.41 post–layout simulation results and experimental evidence are included to confirm all the theory.

Key words: Third–order quadrature oscillator, Cadence IC Design Tools, Layout

Novi kvadraturni oscilator trećeg reda s uzemljenim kondenzatorima. U ovom radu prikazana su dva kvadratična oscilatora trećeg reda (TOQO) zasnovana na strminskim pojačalima diferenciranja struja (CDTA), korištena u strujnom režimu bez otpornika uz promjenjivu frekvenciju. Predloženi TOQO-ovi sastoje se od najmanjeg mogućeg broja aktivnih i pasivnih komponenti, osobito prva inačica TOQO-a, u kojoj su korištena samo dva CDTA-a i tri kondenzatora. TOQO-ovi ne posjeduju niti jedan otpornik, dok su svi kondenzatori korišteni u TOQO-ovima uzemljeni, što je idealno za monolitnu integraciju. Uvjet osciliranja (CO) i frekvencija osciliranja (FO) TOQO-ova može biti upravljana elektronički i nezavisno, što ih čini pogodnima za oscilatore promjenjive frekvencije (VFO). Nadalje, dva TOQO-a mogu isporučivati četiri eksplicitna kvadratična strujna izlaza na priključku visoke izlazne impedancije, te mogu biti u direktnoj kaskadi s drugim krugovima u strujnom režimu bez ikakvih zahtjeva na poklapanje impedancija. Simulacijski rezultati za prikazane sheme dobiveni su korištenjem Cadence IC Design Tools 5.1.41 alata, a uključeni su i eksperimentalni pokazatelji kako bi se potvrdila sva prikazana teorijska osnova.

Ključne riječi: Kvadraturni oscilator trećeg reda, Cadence IC Design Tools, Shema

1 INTRODUCTION

Sinusoidal oscillators are very important analog building block in communication, analog signal processing, control, instrumentation and measurement systems [1]. During the past decades, the current–mode approach has become more popular in analog integrated circuit design due to its advantages of providing larger dynamic range, wider bandwidth, and lower power consumption over the voltage–mode counterparts [2]. Several of active current mode blocks are proposed for active filters, oscillators and immittances circuit design. The current–mode realization of oscillators and filters using the first generation of current conveyor (CCI), the second generation of current conveyor (CCII), current differencing buffer amplifier (CDBA) and many other active blocks have been reported in [3–5]. However, a large number of passive resistors are inevitably used in these circuits (except for the resistors that support linear capacitors), which are not suitable for monolithic integration. In 2003, D. Biolek proposed the current differencing transconductance amplifier [6], which is the synthesis of CDU (current differencing unit) and OTA, and it is a really current–mode element whose inputs and outputs are all current form. The CDTA can be used as active block in analog circuit design with minimum number of resistors.

Quadrature oscillators are widely used in quadrature mixers, single–sideband modulators and all kinds of communication systems, and they have received considerable attention. Especially, the four–phases quadrature oscillators are suitable for the sub–harmonic mixer to reduce the noise and inter–modulation distortion [7–8]; and the multi–phases oscillators can be used in sub–harmonically pumped frequency conversion circuits [9].The mostly reported works are two integrator loop second–order quadrature oscillators and all–pass filter–based second–order quadrature oscillators [10–21], however, the CO and FO of the third–order quadrature oscillators usually can be controlled electronically and independently, they are more suitable for variable frequency oscillator, and they are more suitable for practice use [22–28].

This paper presents two CDTA–based current–mode resistors–less variable frequency TOQOs, and the proposed circuits can provide the following advantageous features:

1. The proposed circuits employ only grounded capacitors, and which are in accordance with the point of view of integrated circuit implementation as grounded capacitor circuits can compensate for the stray capacitances at their nodes.
2. The proposed circuits are completely resistor–less, which are suitable for monolithic integration.
3. The CO and FO of the two TOQOs can be controlled electronically and independently, which make them suitable for VFO.
4. All the proposed two TOQOs can provide four explicit quadrature current outputs at high output impedance terminals, which facilitate cascading with other current–mode circuits without any impedance matching requirements.

The characteristics of the proposed TOQOs compared with other works are listed in Table 1. From Table 1, it is clear that the proposed TOQOs realize four explicit quadrature current outputs at high output impedance terminals with electronically and independently controllable of CO and FO using minimum number of passive and active elements.

2 THEORY AND PRINCIPLE

2.1 Current Differencing Transconductance Amplifier

Fig.1 (a) shows the symbol of CDTA. The terminal relation of the CDTA can be characterized by the following equations [10]:

$$\begin{aligned} & v_p = v_n = 0 \\ & i_z = i_p - i_n \\ & \pm i_x = \pm g_m v_z = \pm g_m Z_Z i_Z \end{aligned} \tag{1}$$

In Fig.1 (a), p and n are the input terminals, z and x are the output terminals, g_m is the transconductance gain, and Z_z is the external impedance connected to the terminal Z. From equation (1), the current i_z is the difference of the currents at p and n (i_p-i_n), and it flows from the terminal z into the impedance Z_z. The voltage at the terminal z is transferred to a current at the terminal x (i_x) by a transconductance gain (g_m), which can be electronically controlled by an external bias current I_B.

Table 2. Dimension of the CMOS transistors

	W(μm) / L(μm)
NMOS transistors	
M_a, M_1 – M_7, M_{33} – M_{39}	5μm / 0.5μm
M_{12} – M_{15}	5μm / 0.35μm
M_{24} and M_{25}	10μm / 0.4μm
M_b	10μm / 0.18μm
PMOS transistors	
M_8 – M_{11}	5μm / 0.35μm
M_{16} – M_{23}	5μm / 0.18μm
M_{26} – M_{32}	5μm / 0.5μm

Fig.1 (b) is the non–ideal model of CDTA. R_p and R_n are the series input parasitic resistances at terminals p and n, respectively. (R_z // C_z) and (R_x // C_x) are the grounded output parasitic impedances at terminals z and x.

Figure 2 is the CDTA used in this work, and the channel dimensions of the transistors are shown in Table 2. The parasitic resistances (R_p and R_n) and the transconductance (g_m) of the CDTA can be expressed as [15]:

$$R_p = R_n = \sqrt{\frac{1}{8\mu_n C_{ox} \frac{W_{10}}{L_{10}} |I_{b1}|}} \tag{2}$$

$$g_m = \sqrt{\mu_n C_{ox} \frac{W_{25}}{L_{25}} |I_{b2}|} \tag{3}$$

2.2 The proposed third–order Quadrature Oscillators

The first proposed TOQO is shown in Fig.3. Because the parasitic resistance of p terminal of $CDTA_1$ is used as an active resistor in this circuit, this TOQO only consists of two CDTAs and three grounded capacitors, and it contains the minimum number of active and passive components of all the reported TOQOs.

Using equation (1), a routine analysis of the circuit yields the following characteristic equation:

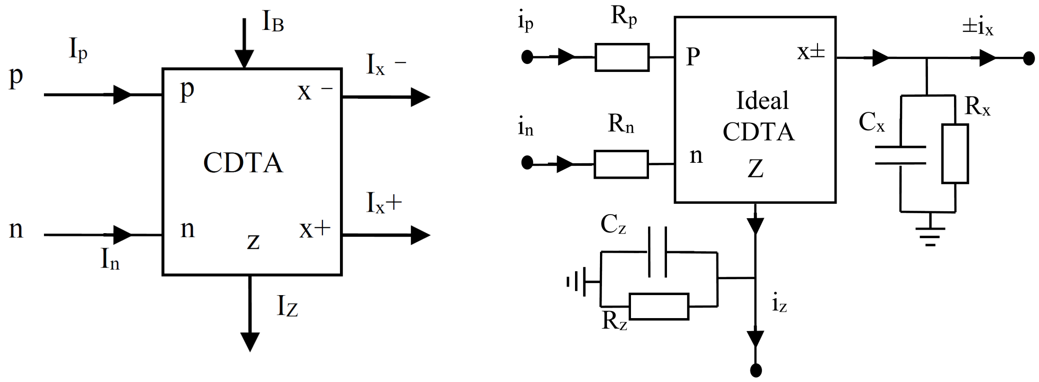
$$s^3 R_{p1} C_1 C_2 C_3 + s^2 C_1 C_2 + s g_{m1} C_2 + g_{m1} g_{m2} = 0 \tag{4}$$

From equation (4), the CO and FO can be expressed as:

$$C_2 = g_{m2} R_{p1} C_3 \tag{5}$$

Table 1. The performance comparison table

Ref	**Active element**	**Number of active elements**	**Electronically and independently control for CO and FO**	**Number of R+C**	**Number of quadrature outputs**	**Outputs at high output impedance terminals**
19	OTA	3	No	>3	2	No
20	CCII	4	Yes	3	4	Yes
21	CCII	3	No	3+3	2	No
22	CCII	3	Yes	3	4	Yes
23	CDTA	3	No	3	2	Yes
24	CDTA	3	Yes	3	2	Yes
25	~	~	No	6	4	No
This work	CDTA	2	Yes	3	4	Yes
	CDTA	3	Yes	3	4	Yes



(a) Symbol for the CDTA (b) Non–ideal model of the CDTA

Fig. 1. Symbol and Non–ideal model of CDTA

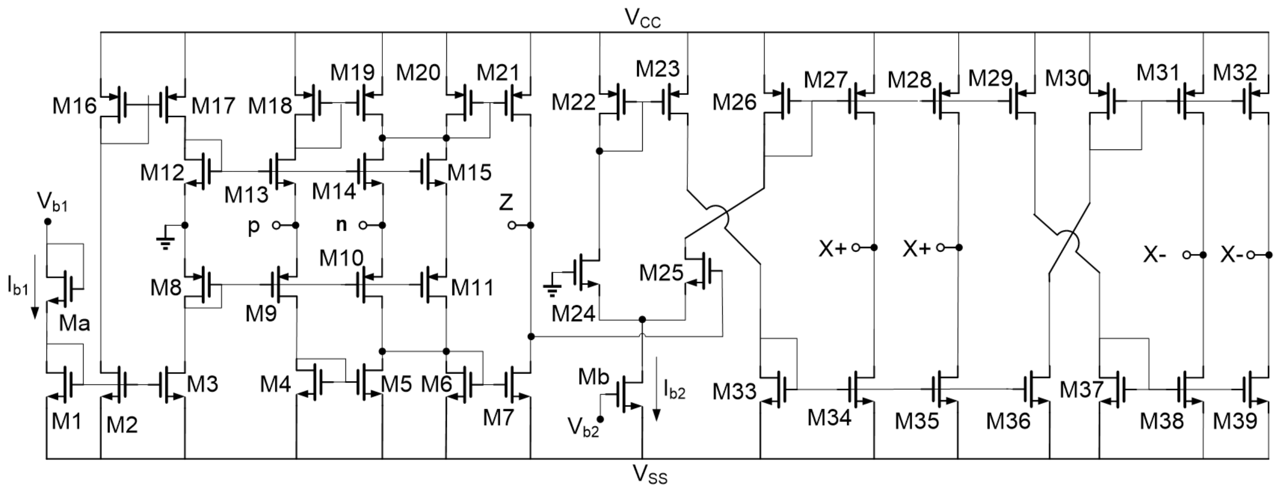


Fig. 2. The CDTA in this work

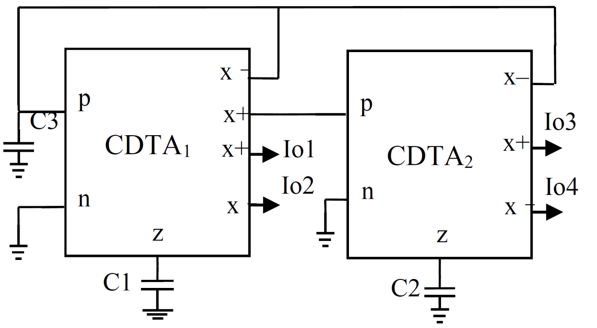


Fig. 3. The first proposed TOQO

$$\omega_o = \sqrt{\frac{g_{m1}}{R_{p1}C_1C_3}} \tag{6}$$

From (5) and (6), it is clear that the FO can be controlled by g_{m1}, and the CO can be independently controlled by g_{m2}. This is a big advantage of the proposed oscillator, and which make the oscillator suitable as VFO.

From Fig. 3, the current transfer function between I_{o1} and I_{o3} is:

$$\frac{I_{o3}(s)}{I_{o1}(s)} = \frac{g_{m2}}{sC_2} \tag{7}$$

When the oscillator works at steady state, equation (7) becomes [12]:

$$\frac{I_{o3}(j\omega_o)}{I_{o1}(j\omega_o)} = \frac{g_{m2}}{\omega_o C_2}e^{-j90^o} \tag{8}$$

This means that the phase difference between I_{o1} and I_{o3} is 90°, the two currents are quadrature.

Also, because of the multiple–output CDTAs, the circuit can provide two inverted output currents i_{o2} and i_{o4}. Thus, the relations of all the output currents can be expressed as:

$$\begin{aligned} i_{o1} &= -i_{o2} \\ i_{o3} &= -i_{o4} \end{aligned} \tag{9}$$

This means that the circuit can provide four explicit quadrature current outputs.

The second proposed TOQO is shown in Fig.4, and it consists of three CDTAs and three grounded capacitors.

Using the similar analysis method above, the characteristic equation, CO and FO of the second proposed third–order QO can be express as:

$$s^3C_1C_2C_3+s^2g_{m2}C_1C_3+sg_{m1}g_{m2}C_3+g_{m1}g_{m2}g_{m3} = 0 \tag{10}$$

$$g_{m2}C_3 = g_{m3}C_2 \tag{11}$$

$$\omega_o = \sqrt{\frac{g_{m1}g_{m2}}{C_1C_2}} \tag{12}$$

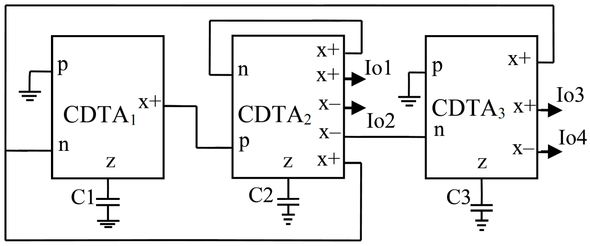


Fig. 4. The second proposed TOQO

From (11) and (12), it is clear that the FO can be controlled by g_{m1}, and the CO can be independently controlled by g_{m3}, so, the CO and FO of the oscillator can also be electronically and independently controlled.

3 NON–IDEAL ANALYSIS

Using the non–ideal model in Fig.1 (b), the transfer errors of CDTA can be expressed as:

$$\begin{aligned} i_z &= \alpha_p i_p - \alpha_n i_n \\ i_x+ &= \beta g_m V_z \\ i_x- &= -\gamma g_m V_z \end{aligned} \tag{13}$$

where $\alpha_p = 1-\varepsilon_p$ is the current tracking error from terminal p to z, $\alpha_n = 1-\varepsilon_n$ is the current tracking error from terminal n to z, β is transconductance inaccuracy factor from the z to $x+$ terminals, and γ is transconductance inaccuracy factor from the z to x terminals of the CDTA, respectively.

Considering the tracking errors and taking the parasitics into account, the modified characteristic equation of the first TOQO can be rewritten as:

$$\begin{aligned} &s^3R_{p1}C_1'C_2'C_3'+s^2\Big(C_1'C_2'+R_{p1}G_{z1}C_2'C_3'+R_{p1}G_{z2}C_1'C_3'\Big) \\ &+s\Big(\alpha_{p1}\beta_1 g_{m1}C_2'+R_{p1}G_{z1}G_{z2}C_3'+G_{z1}C_2'+G_{z2}C_1'\Big) \\ &+(\alpha_{p1}\alpha_{p2}\beta_1\gamma_2 g_{m1}g_{m2}+G_{z1}G_{z2}) = 0 \end{aligned} \tag{14}$$

where α_{pi} , α_{ni}, β_i and γ_i are the parameters α_p, α_n, β and γ of the i–th CDTA, $C_1' = C_1+C_{z1}$, $C_2' = C_2+C_{z2}$, $C_3' = C_3+C_x$, $G_{z1} = \frac{1}{R_{z1}}$, $G_{z2} = \frac{1}{R_{z2}}$, respectively.

The non–ideal CO and FO of the first third–order QO can be rewritten as:

$$\begin{aligned} &\frac{\alpha_{p1}\alpha_{p2}\beta_1\gamma_2 g_{m1}g_{m2}+G_{z1}G_{z2}}{C_1'C_2'+R_{p1}G_{z1}C_2'C_3'+R_{p1}G_{z2}C_1'C_3'} \\ &= \frac{\alpha_{p1}\beta_1 g_{m1}C_2'+R_{p1}G_{z1}G_{z2}C_3'+G_{z1}C_2'+G_{z2}C_1'}{R_{p1}C_1'C_2'C_3'} \end{aligned} \tag{15}$$

$$\omega_0' = \sqrt{\frac{\alpha_{p1}\beta_1 g_{m1}C_2'+R_{p1}G_{z1}G_{z2}C_3'+G_{z1}C_2'+G_{z2}C_1'}{R_{p1}C_1'C_2'C_3'}} \tag{16}$$

All the active and passive sensitivities of the first TOQO are low, which can be expressed as:

$$\begin{aligned}&S^{\omega_0^{'}}_{\alpha_{p1},\beta_1,g_{m1}} \approx \tfrac{1}{2}; S^{\omega_0^{'}}_{C_1,C_3,R_{p1}} = -\frac{1}{2};\\ &S^{\omega_0^{'}}_{\alpha_{n1},\alpha_{n2},\alpha_{p2},R_{n1},R_{n2},R_{p2},\beta_2,\gamma_2,g_{m2},C_2} = 0\end{aligned} \tag{17}$$

Because R_{z1} and R_{z2} are relatively large, $G_{z1} = G_{z2} \approx 0$. The non–ideal CO and FO of the first third–order QO can be expressed as:

$$\frac{\alpha_{p2}\gamma_2 g_{m2}}{C_2^{'}} = \frac{1}{R_{p1}C_3^{'}} \tag{18}$$

$$\omega_o^{'} = \sqrt{\frac{\alpha_{p1}\beta_1 g_{m1}}{R_{p1}C_1^{'}C_3^{'}}} \tag{19}$$

From (18) and (19), we can know that both of the CO and FO of the first third–order QO are affected by the tracking errors, transconductance inaccuracy factor of the negative and positive signal paths and the parasitics of CDTA. Considering these facts, the layout of the TOQO should be designed as symmetrically as possible to minimize the mismatch in the signal paths to eliminate these non–ideal parameters. Considering these facts and make it possible in practice, the deviations are very small, and the CO and FO can also be electronically and independently controlled by g_{m1} and g_{m2}. Moreover, from (6) and (19), because of the tracking errors, transconductance inaccuracy factor of the negative and positive signal paths ($\alpha \leq 1$, $\beta \leq 1$, $\gamma \leq 1$), the oscillation frequency of the first TOQO will decrease below its theoretical value.

The modified characteristic equation of the second TOQO is:

$$\begin{aligned}&s^3C_1^{'}C_2^{'}C_3^{'} + s^2\alpha_{n2}\gamma_2 g_{m2}C_1^{'}C_3^{'}\\ &+s\alpha_{n1}\alpha_{p2}\beta_1\gamma_2 g_{m1}g_{m2}C_3^{'}\\ &+\alpha_{n1}\alpha_{n3}\alpha_{p2}\beta_1\gamma_2\beta_3 g_{m1}g_{m2}g_{m3} = 0\end{aligned} \tag{20}$$

where $C_1^{'} = C_1 + C_{z1}$, $C_2^{'} = C_2 + C_{z2}$, $C_3^{'} = C_3 + C_{z3}$, respectively.

The non–ideal CO and FO of the second TOQO are:

$$\alpha_{n2}\gamma_2 g_{m2}C_3^{`} = \alpha_{n3}\beta_3 g_{m3}C_2^{`} \tag{21}$$

$$\omega_o^{`} = \sqrt{\frac{\alpha_{n1}\alpha_{p2}\beta_1\gamma_2 g_{m1}g_{m2}}{C_1^{`}C_2^{`}}} \tag{22}$$

All the active and passive sensitivities of the second TOQO are low, which can be expressed as:

$$\begin{aligned}&S^{\omega_0^{'}}_{\alpha_{n1},\alpha_{p2},\beta_1,\gamma_2,g_{m1},g_{m2}} = \frac{1}{2}; S^{\omega_0^{'}}_{C_1,C_2} = -\frac{1}{2};\\ &S^{\omega_0^{'}}_{\alpha_{n2},\alpha_{n3},\alpha_{p1},\alpha_{p3},\beta_2,\beta_3,\gamma_1,\gamma_3,g_{m3},C_3} = 0\end{aligned} \tag{23}$$

From (21)–(22), we can know that both of the CO and FO of the second third–order QO are also affected by the tracking errors, transconductance inaccuracy factor of the negative and positive signal paths and the parasitics of CDTA. Considering these facts, the layout of the TOQO should also be designed as symmetrically as possible to minimize the mismatch in the signal paths to eliminate these non–ideal parameters. From (21)–(22), we can also know that the FO can be controlled by g_{m1}, and the CO can be independently controlled by g_{m3}, and the CO and FO of the second TOQO can also be electronically and independently controlled in the non–ideal analysis. Moreover, from (12) and (22), because of the tracking errors, transconductance inaccuracy factor of the negative and positive signal paths ($\alpha \leq 1$, $\beta \leq 1$, $\gamma \leq 1$), the oscillation frequency of the second TOQO will also decrease below its theoretical value.

From (18)–(22), we can know that the CO and FO of the two proposed TOQOs are all affected slightly by the tracking errors, transconductance inaccuracy factor of the negative and positive signal paths and the parasitics of CDTA. In practice, the CDTAs and their layouts should be designed as symmetrically as possible for minimizing these errors.

4 POST–LAYOUT SIMULATION RESULTS

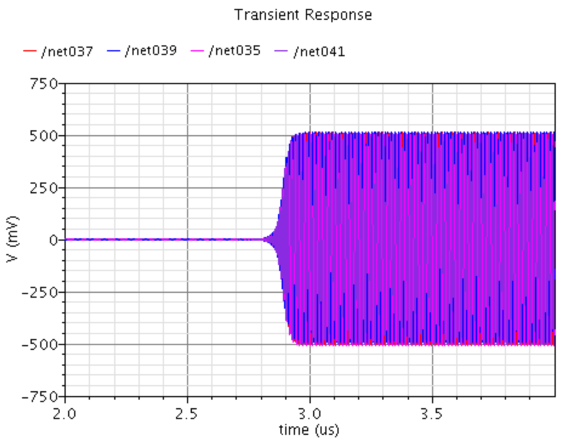
The CDTA is realized in Fig.2; The performance of proposed circuits are verified using Cadence IC Design Tools 5.1.41 with standard Chartered $0.18\,\mu$m CMOS process. The supply voltages are VCC $= -$VSS $= 2.5\,$V.

The post–layout simulation results of the first TOQO in Fig.3 are presented in Fig.5. Fig.5 (a) is the simulated i_{o1}, i_{o2}, i_{o3} and i_{o4} during initial state, and Fig.5(b) is the simulated quadrature outputs i_{o1}, i_{o2}, i_{o3} and i_{o4} at steady state.

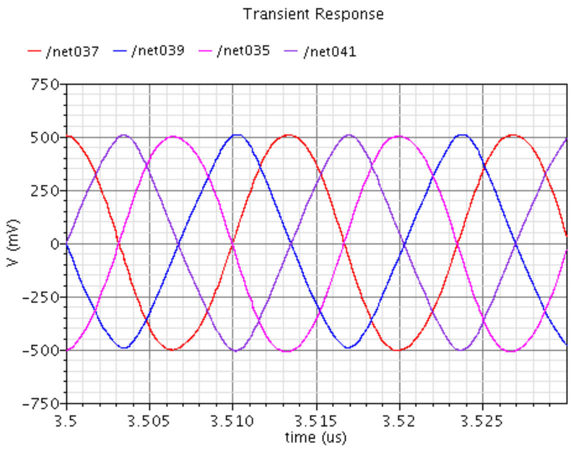
The capacitors are $C_1 = 6\,$pF, $C_2 = 5\,$pF, $C_3 = 7\,$pF. The bias currents of CDTA$_1$ and CDTA$_2$ are $I_{b1} = 750\,\mu$A, $I_{b2} = 1.1\,$mA. Using equations (2)–(3), it is easy to know that the parasitic resistances $R_p = R_n = 478\,\Omega$, $g_{m1} = g_{m2} = 5.25 \times 10^{-3}\,$A/V. The ideal theory frequency of the first TOQO should be $81\,$MHz, while the simulated frequency of the oscillation is found to be $73.6\,$MHz, and the frequency deviation is about 8%.

The post–layout simulation results of the second TOQO in Fig.4 are presented in Fig.6. Fig. 6(a) is the simulated i_{o1}, i_{o2}, i_{o3} and i_{o4} during initial state, Fig.6 (b) is the simulated quadrature outputs i_{o1}, i_{o2}, i_{o3} and i_{o4} at steady state.

The value of the capacitors are $C_1 = 4\,$pF, $C_2 = 3\,$pF, $C_3 = 6\,$pF. The bias currents of CDTA$_1$, CDTA$_2$ and

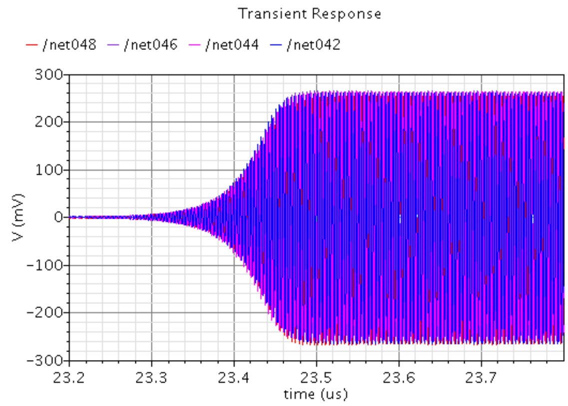


(a) v_{o1}, v_{o2}, v_{o3} and v_{o4} at steady state

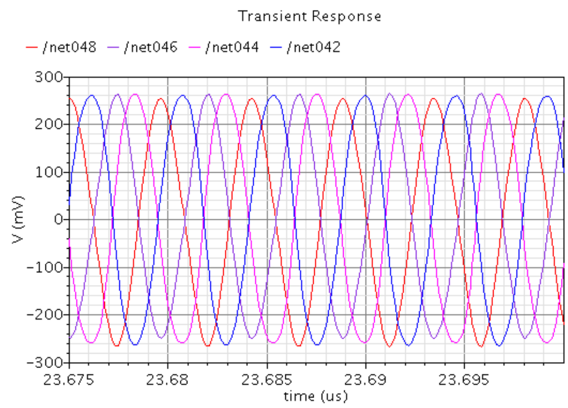


(b) v_{o1}, v_{o2}, v_{o3} and v_{o4} during initial state

Fig. 5. The simulated quadrature outputs of the first TOQO



(a) v_{o1}, v_{o2}, v_{o3} and v_{o4} during initial state



(b) v_{o1}, v_{o2}, v_{o3} and v_{o4} at steady state

Fig. 6. The simulated quadrature outputs of the second TOQO

CDTA$_3$ are $I_{b1} = 800\,\mu$A, $I_{b2} = 1\,\mu$A. Using equation (3), it is easy to know that $g_{m1} = g_{m2} = 5.3 \times 10^{-3}$ A/V. The ideal theory frequency of the second TOQO should be 241 MHz, while the simulated frequency of the oscillation is found to be 212 MHz, and the frequency deviation is about 10%.

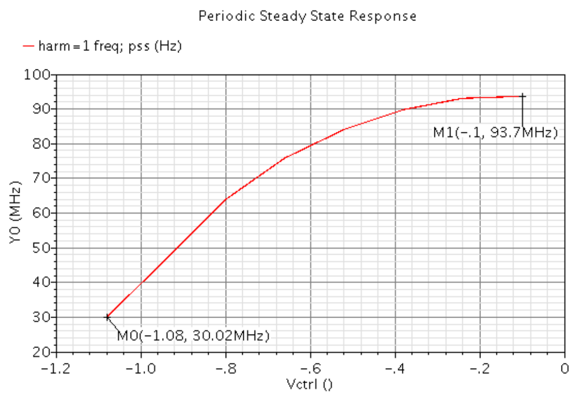
Fig.7 (a) and (b) are the output frequency versus the bias voltage of the TOQOs. From Fig. 7(a), it is clear that the output frequency of the first TOQO can be changed from 30.02 MHz to 93.7 MHz by controlling V_{b2} from -1.08 V to -0.1 V, and the frequency tuning range is 63.68 MHz. From Fig.7 (b), it is clear that the output frequency of the second TOQO can be changed from 84.16 MHz to 229.3 MHz by controlling V_{b2} from -1.148 V to -0.1 V, and the frequency tuning range is 145.14 MHz.

Fig.8 (a) and (b) are the layouts of the two proposed TOQOs. The first TOQO in Fig.8(a) takes a compact chip area of $1.0mm^2$ and the second TOQO in Fig.9(b) takes a compact chip area of $1.44mm^2$ including the test pads.

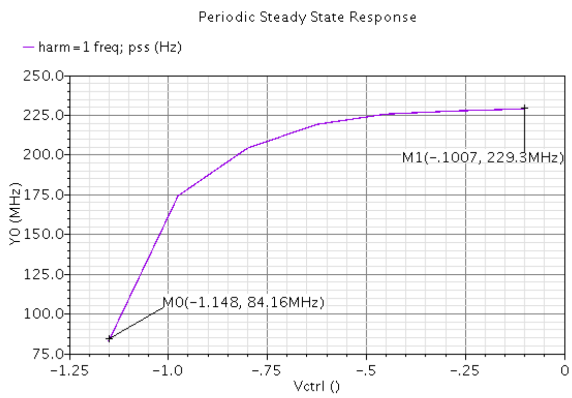
5 EXPERIMENTAL EVIDENCE

In order to further verifying the correctness of the proposed TOQOs, the circuit in Figure 3 is verified in the laboratory with commercially available ICs. The CDTAs are realized using AD844 and CA3080 in Fig.9, the two AD844 ICs consist of the CDU. The two CA3080 ICs are the transconductance section, and they realize $\pm i_x = \pm g_m V_z$.

The capacitors are $C_1 = 10$ nF, $C_2 = 1$ nF, $C_3 = 10$ nF, and the supply voltages VCC $= -$VSS $= 12$ V. Fig.10 are the experimental results of the output waveforms, and all the outputs are measured using load resistors $R_L = 1\,\mathrm{K}\Omega$. The input parasitic resistance of CDTA$_1$ is about $70\,\Omega$ [29], and the transconductance of CDTA$_1$ is about $9500\,\mu$S [30], the ideal frequency of the

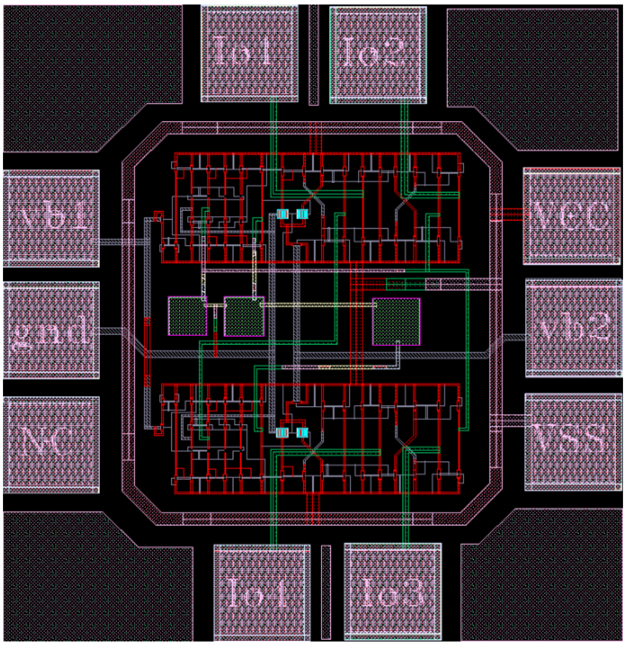


(a) The output frequency versus the bias voltage of the first TOQO

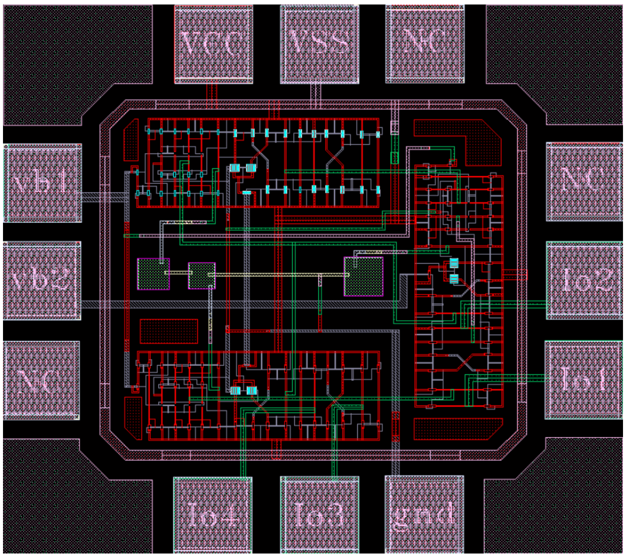


(b) The output frequency versus the bias voltage of the second TOQO

Fig. 7. The output frequency versus the bias voltage of the TOQOs



(a) The layout of first TOQO in Fig.3 ($1.0 \times 1.0mm^2$)



(b) The Layout of second TOQO in Fig.4 ($1.2 \times 1.2mm^2$)

Fig. 8. The layouts of the two TOQOs

QO should be 185 KHz, and the output frequency is found to be 121.6 KHz.

6 CONCLUSIONS

Two third–order CDTA–based current–mode resistors–less variable frequency QOs are presented in this paper. The proposed TOQOs only consist of CDTAs and grounded capacitors, and they are completely resistor–less, which are ideal for monolithic integration. The CO and FO of the two TOQOs can be controlled electronically and independently, which make them suitable for VFO in different applications. All the circuits can provide four explicit quadrature current outputs at high output impedance terminals, and they can be connected directly to the next stage without any impedance matching requirements.

7 ACKNOWLEDGMENT

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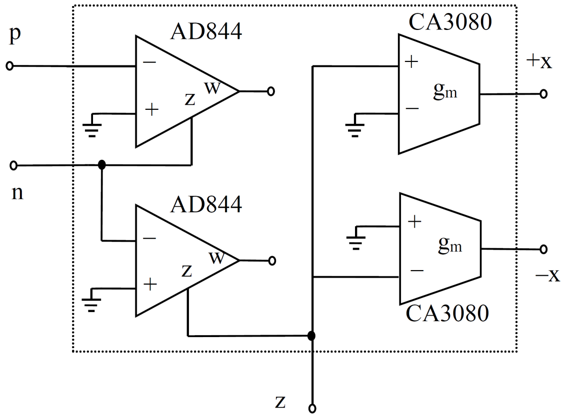

Fig. 9. Possible implementation of CDTA using commercially available Ics

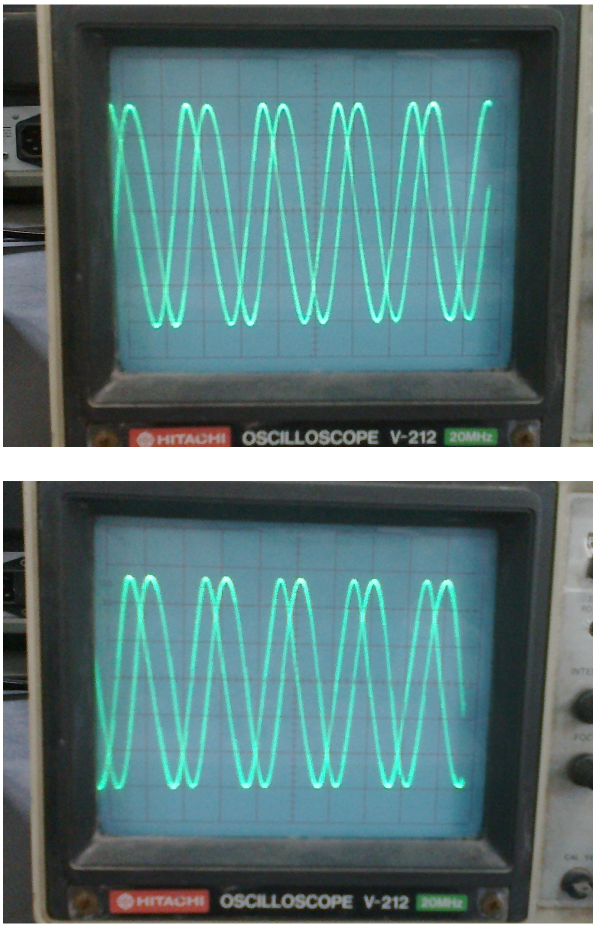

Fig. 10. Experimental evidence of the quadrature outputs

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