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Low-frequency quadrature sinusoidal oscillators using current differencing buffered amplifiers

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This paper proposes new realizations of low-frequency quadrature sinusoidal oscillators using CDBA (current differencing buffered amplifier) as the active building block (ABB). The proposed circuits employ reduced number of components, namely two CDBAs, four (or five) resistors and two true/virtually grounded capacitors. The oscillators provide two quadrature voltage outputs and the condition of oscillation (CO) and the frequency of oscillation (FO) are independently controllable. Low frequency generation is enabled by the presence of difference term in the numerator of FO. The non-ideal analysis and sensitivity study of the circuits have been carried out and the circuits exhibit satisfactory sensitivity performance. SPICE simulation results are included that validate the working of the circuit.

Keywords: Quadrature oscillator, Low-frequency oscillator, Current differencing buffered amplifier, Dual-current-controlled current differencing buffered amplifier

1 Introduction

The recently proposed active building block (ABB), namely the current differencing buffered amplifier [1] (CDBA), has been found to be versatile for both voltage-mode (VM) and current-mode (CM) signal processing and its use has reportedly provided several circuit solutions. These primarily consist of the design of leapfrog filters[2], universal bi-quad filters[3-6], active inductor simulators[7] and first-order all-pass filtering sections[8,9]. The CDBA has also been used to create sinusoidal oscillators[10-15]. But the proposed circuit[10] uses excessive number of passive components, namely four resistors and four capacitors. The proposed circuit[11] reduces the number of resistors to three, but still, uses three capacitors to realize a second-order oscillator. The oscillator[12,13] uses two grounded capacitors, but uses four resistors. The realizations of oscillators with reduced number of components, particularly those providing independent control of the condition of oscillation (CO) and the frequency of oscillation (FO) by two separate resistors, have received considerable attention and two of the recently reported CDBA oscillators[14,15] use canonic number of components, viz. two CDBAs, three resistors and two capacitors. In one of the more recent works[16], a catalogue of such "single-resistance-controlled oscillators" (SRCOs) has been proposed using true/virtually grounded capacitors. Although great emphasis has been given to the design of SRCOs using CDBAs, the design of low-frequency oscillators (LFOs) governed by the tuning laws[17] is hitherto investigated using CDBA. LFOs are important circuits, especially useful in biological and biomedical applications[18]. Creating LFOs using the SRCO-type tuning laws[14-16] would require unusually large values of resistors and capacitors, leading to a great demand of area. An alternative technique is to use reasonable valued passive components, while modifying the circuit so as to get a difference term in the numerator of the FO. Since CDBA constitutes of a current differencing unit (CDU) in its front-end, it is ideal for realizing LFOs governed[17]. In this work, new CDBA based VLFOs have been proposed which have the following advantageous features:

(i) The circuits employ reduced number of active and passive components, namely only two CDBAs, four (or five) resistors and two true/virtually grounded capacitors.
(ii) The use of grounded capacitors makes the circuits suitable for monolithic integration as grounded capacitor circuits can compensate for the stray capacitances at their nodes[19,20].
(iii) The circuits enjoy non-interactive (independent) control of the condition of oscillation (CO) and the frequency of oscillation (FO) by means of different resistors. Hence, the circuits can also be classified as SRCOs.
(iv) The circuits are quadrature oscillators (QOs) in voltage-mode, i.e. providing buffered voltage

outputs of two sinusoids which are 90° phase shifted. QOs have wide applications in signal processing, communication systems (e.g. quadrature mixers and single-sideband modulators), and power controller and instrumentation systems[20,21].

(v) The FO can be electronically tuned by replacing the control resistor by an electronically resistor, for e.g. by a MOSFET working in triode-region.

(vi) The circuits exhibit low f_o active and passive sensitivities.

With all the above stated advantages, the proposed circuits add to the present repertoire of CDBA based oscillators and serve to be the first CDBA-based LFOs.

2 Proposed Circuits

The current differencing buffered amplifier (CDBA) is an active building block (ABB), ideally characterized by the following equations:

$$V_p = V_n = 0,\ I_z = I_p - I_n,\ V_w = V_z \qquad \ldots(1)$$

The circuit symbol of CDBA is shown in Fig. 1. The bipolar and MOS implementations of CDBA could be found in Refs (22, 7), respectively. Although, the CDBA is currently not available as off-the-shelf component, but it can be constructed using com-mercially available current-feedback-amplifiers[10-15] (e.g. AD844AN).

2.1 Type 1

The first type of the proposed QOs is shown in Fig. 2. The circuit shown in Fig. 2(a) is derived[14] from the SRCO. The lossless integrator[14] is modified so that it features a difference term in the numerator of its transfer function. Using Eq. (1) and doing the routine analysis of the circuit yields the following characteristic equation:

$$\begin{aligned} &s^2C_1C_2R_1R_2R_3R_4 + sC_2R_2R_4(R_1 - R_3) \\ &\quad + R_1(R_4 - R_3) = 0 \end{aligned} \qquad \ldots(2)$$

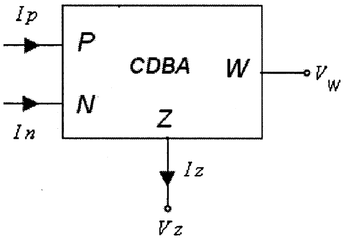

Fig. 1—Circuit symbol of CDBA

From Eq. (2), the CO and the FO are given as:

$$\text{CO: } R_1 \le R_3 \qquad \ldots(3)$$

$$\text{FO: } f_o = \frac{1}{2\pi}\sqrt{\frac{R_4 - R_3}{C_1C_2R_2R_3R_4}} \qquad \ldots(4)$$

It is evident from Eqs (3) and (4) that CO can be controlled by R_1 and FO is independently controllable by R_2 and/or R_4. This dual/twin resistor control of FO is not available[10-16]. More interestingly, the presence of difference term in the numerator of FO enables low frequency generation. We break resistor R_4 into two parts: a fixed part identical to R_3 and another as variable resistor (tunable by any means). Considering

$$R_4 = R_3 + R_\Delta \text{ or } R_3 = R_4 - R_\Delta \qquad \ldots(5)$$

Eq. (4) can be rewritten as:

$$\text{FO: } f_o = \frac{1}{2\pi}\sqrt{\frac{R_\Delta}{C_1C_2R_2R_3(R_3 + R_\Delta)}} \qquad \ldots(6)$$

Ideally, under the limiting case that $R_\Delta \to 0$, $\lim_{R\Delta \to 0} f_0 = 0$ and hence, very low frequencies can be achievable. However, it is investigated how the device non-idealities restrict the minimum potential. The sensitivity analysis using Eq. (5) indicates that:

$$\begin{aligned} &|S^{f_o}{}_{C1,C2,R2}| = \frac{1}{2},\ |S^{f_o}{}_{R\Delta}| = \frac{R_3}{2(R_3 + R_\Delta)}, \\ &|S^{f_o}{}_{R3}| = \frac{2R_3 + R_\Delta}{2(R_3 + R_\Delta)} \end{aligned} \qquad \ldots(7)$$

All values are less than unity in magnitude except for the last term which is indicative of satisfactory sensitivity performance. The two quadrature voltage outputs have been marked in the circuit diagram in Fig. 2 and are related as:

$$V_{o2} = -jk_1V_{o1}$$

where

$$k_1 = \frac{1}{\omega_o C_2}\left(\frac{1}{R_3} - \frac{1}{R_4}\right) = \frac{R_\Delta}{\omega_o C_2 R_3(R_3 + R_\Delta)} \qquad \ldots(8)$$

It should also be noted that R_4 can be used either as a single variable resistor or as a series of a fixed resistor and another variable resistor. In either of the cases Eq. (5) has to be satisfied, so as to get reduced f_o

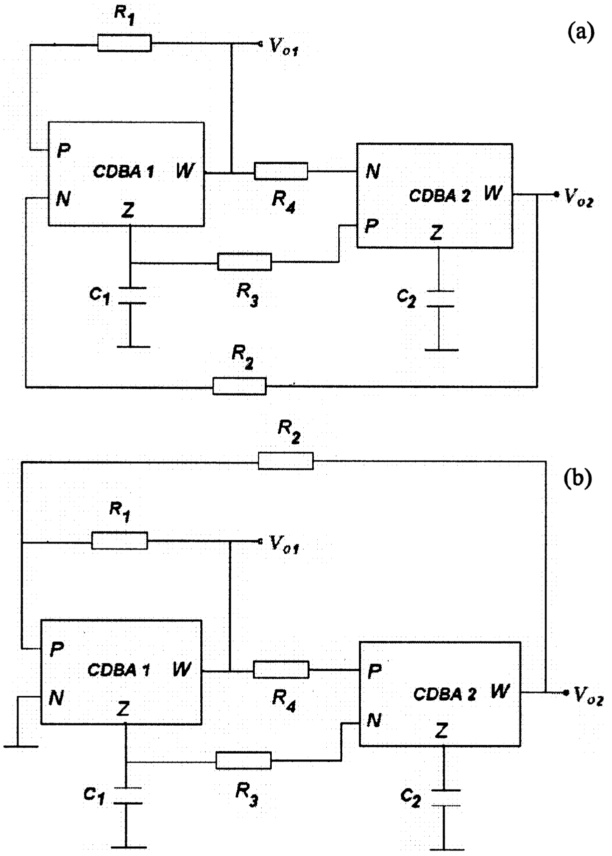

Fig. 2 — Proposed CDBA-based quadrature LFOs : Fig. 2(a) is derived from Ref.(14)

sensitivity value according to Eq. (7). Electronically controlled variable resistors can also be employed to provide electronic control of the FO (which can be desirable in several tuning applications like automatic amplitude control). Voltage-controlled resistors[23] (VCRs) or resistors simulated using operational transconductance amplifier (OTA) can be used for this purpose.

2.2 Type 2

The second type of the proposed QO is shown in Fig. 3. The circuit has been derived from Circuit D proposed[16]. Again using Eq. (1) and doing the routine analysis of the circuit yields the following characteristic equation:

$$s^2C_1C_2R_1R_2R_3R_4 + sC_2R_3R_4(R_1 - R_2) + R_2(R_4 - R_3) = 0 \qquad \ldots(9)$$

From Eq. (9), the CO and the FO are given as:

$$\text{CO: } R_1 \le R_2 \qquad \ldots(10)$$

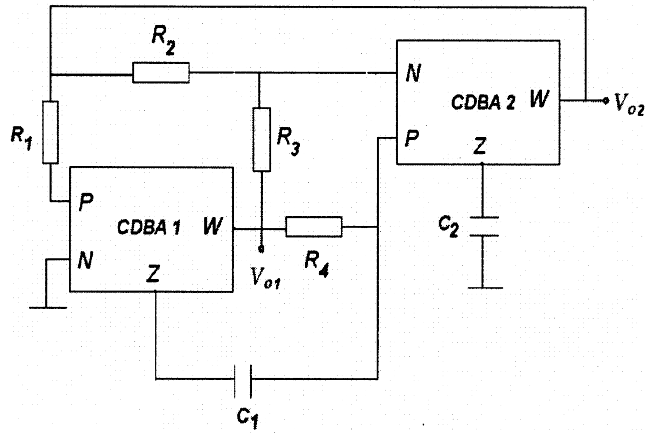

Fig. 3— Proposed CDBA-based quadrature LFO derived from Ref.(16)

$$\text{FO: } f_o = \frac{1}{2\pi}\sqrt{\frac{R_4 - R_3}{C_1C_2R_1R_3R_4}} \qquad \ldots(11)$$

It is evident from Eqs (10) and (11) that the CO and the FO can be controlled independently by R_2 and R_3/R_4, respectively. If we consider $R_4 = R_3 + R_\Delta$, Eq. (11) can be rewritten as :

$$\text{FO: } f_o = \frac{1}{2\pi}\sqrt{\frac{R_\Delta}{C_1C_2R_2R_3(R_3 + R_\Delta)}} \qquad \ldots(12)$$

The sensitivity analysis of Eq. (12) using Eq. (5) gives the same value of $S_{R\Delta}^{f_o}$ as in Eq. (7). The two quadrature voltage outputs have been marked in the circuit diagram in Fig. 2 and are related as:

$$V_{o2} = -jk_2V_{o1}$$

where

$$k_2 = \frac{1}{\omega_o C_1 R_1} \qquad \ldots(13)$$

Clearly, for k_2=1, the two quadrature voltage outputs would have equal amplitudes.

3 Non-Ideal Analysis and Sensitivity Study

For a complete analysis of the circuit, it is important to take into account the non-idealities[11-16] of CDBA. We demonstrate the effects of the non-idealities by considering the circuit in Fig. 2(a) as an example. The following non-idealities have been considered.

In the non-ideal case, the characterizing equation of the CDBA is given as:

$$V_p = V_n = 0,\ I_z = \beta_p I_p - \beta_n I_n,\ V_w = \alpha V_z \qquad \ldots(14)$$

where, β_p and β_n are the current transfer gains from *p* and *n* terminals to *z* terminal, respectively and *α* is the voltage transfer gain from *z* to *w* terminal. These gains differ from their ideal values of unity by current/voltage tracking errors.

The non-zero input resistance at *p* and *n* terminals, denoted by R_p and R_n, respectively. Interestingly, in our circuit all these resistances are absorbed into the external resistor connected at *p* and *n* terminals. Thus, it requires that the external resistors $R_i >> R_{pi/ni}$.

Parasitic capacitance C_z and parasitic resistance R_z appears between the high-output impedance *z* terminal and ground. The use of grounded external capacitors C_1 and C_2 allow easy absorption of the parasitic capacitances C_{z1} and C_{z2}, respectively as they appear in shunt with them. The effects of the parasitic resistances R_{zi} can be alleviated by considering that the operating angular frequency $\omega_o >> \dfrac{1}{(C_i + C_{zi})R_i}$ where *i*=1, 2. This constraint directly limits the low-frequency potential of the LFOs.

Considering the above non-idealities (except the parasitic resistance R_{zi}), the CO and FO for the LFO are modified to:

$$\text{CO: } R_1 + R_{x1} \le \alpha_1 \beta_{p1} (R_3 + R_{x3}) \qquad \ldots(15)$$

$$\text{FO: } f_o = \frac{1}{2\pi}\sqrt{\frac{\alpha_1\alpha_2\beta_{n1}[\beta_{p2}(R_4 + R_{x4}) - \beta_{n2}(R_3 + R_{x3})]}{(C_1 + C_{z1})(C_2 + C_{z2})(R_2 + R_{x2})(R_3 + R_{x3})(R_4 + R_{x4})}} \qquad \ldots(16)$$

To see the effect of the non-idealities on the CO, Eq.(15) is rewritten as:

$$\text{CO: } R_3 \ge (R_1 + R_{x1}) / (\alpha_1 \beta_{p1}) - R_{x3} \qquad \ldots(17)$$

Since α_1, β_{p1} is less than unity in value, Eq. (17) indicates how the required start-up margin for the oscillator has increased as compared to Eq. (3). The value of R_3 must therefore,be chosen appropriately (with appropriate margins) for the start-up of oscillations. Under the optimistic approximation that $\beta_{p1} = \beta_{p2} = \beta_{n1} = \beta_{n2} = \beta$ and $R_{x1} = R_{x2} = R_{x3} = R_{x4} = R_x$, Eq.(16) can be rewritten as:

$$\text{FO: } f_o = \frac{\beta}{2\pi}\sqrt{\frac{\alpha_1\alpha_2(R_4 - R_3)}{(C_1 + C_{z1})(C_2 + C_{z2})(R_2 + R_x)(R_3 + R_x)(R_4 + R_x)}} \qquad \ldots(18)$$

Again using Eq. (5) and doing the sensitivity analysis of Eq. (18), we get :

$$|S^{f_o}_{R\Delta}| = \frac{R_3 + R_x}{2(R_3 + R_x + R_\Delta)}$$

$$|S^{f_o}_{Rx}| = \frac{R_x}{2(R_2 + R_x)} + \frac{R_x}{2(R_3 + R_x)} + \frac{R_x}{2(R_3 + R_\Delta + R_x)}$$

$$|S^{f_o}_{R3}| = \frac{R_3}{2(R_3 + R_x)} + \frac{R_3}{2(R_3 + R_\Delta + R_x)} \qquad \ldots(19)$$

$$|S^{f_o}_{C_1}| = \frac{C_1}{2(C_1 + C_{z1})}$$

$$|S^{f_o}_{C_{z1}}| = \frac{C_{z1}}{2(C_1 + C_{z1})}$$

$$|S^{f_o}_{C_2}| = \frac{C_2}{2(C_2 + C_{z2})} \quad |S^{f_o}_{C_{z2}}| = \frac{C_{z2}}{2(C_2 + C_{z2})} \qquad \ldots(20)$$

All the above mentioned sensitivity values are no more than unity in magnitude and this indicates a satisfactory sensitivity performance of the circuit.

4 Comparative Study

The proposed circuits studied here with the previously reported LFOs in the literature have been compared. The circuits[17] use one ABB (conventional voltage operational amplifier) along with seven resistors and floating capacitors to create LFOs. The passive component count is excessively large as pointed before, the use of floating capacitors is not desirable. The circuit[18] uses a composite active-passive resistor and the resulting circuit is based around Wien-Bridge oscillator, which uses six resistors and floating capacitors. On the contrary, the circuits proposed in this paper use two ABBs, four (or five) resistors (depending on how *R₄* is realized) and two grounded/virtually grounded capacitors. The only apparent drawback can be that CDBA are not commercially available devices and therefore, bread-board implementations are required to be constructed using other commercially available devices. For e.g. CDBA is generally, constructed[10-16] using two AD844AN CFOAs. In such a case, the resulting circuits here would be employing four CFOAs as opposed to only one[17,18].

5 Simulation Results

The working of the proposed oscillator circuits has been verified using SPICE simulations. The QO of Fig. 2(a) has been chosen as the design example here. The CDBA is constructed[10,11] using two CFOAs. The use of CFOA equivalent circuit[10] does not mean that CDBA has a more complex structure than CFOA. Alternatively, bipolar and MOS implementation of the CDBA could also be used. The macro-model of AD844 CFOA by Analog Devices[24] is used for simulations with supply voltages of ±10V. The circuit has been designed with R_1=R_2=10 kΩ and C_1=C_2=5nF. In practice, the value of R_3=10.5 kΩ, which is taken to be greater than R_1 to ensure the start-up of oscillations (i.e. ensuring an appropriate start-up margin by making the roots of the characteristic equation on the RHP) and the value of R_4=13 kΩ. The simulated waveforms of the quadrature voltage outputs V_{o1} and V_{o2} in transient and steady state are shown in Figs 4 and 5, respectively. The simulated frequency of 1.336 kHz is very close to the theoretical value of 1.36 kHz. The ratio of amplitudes of

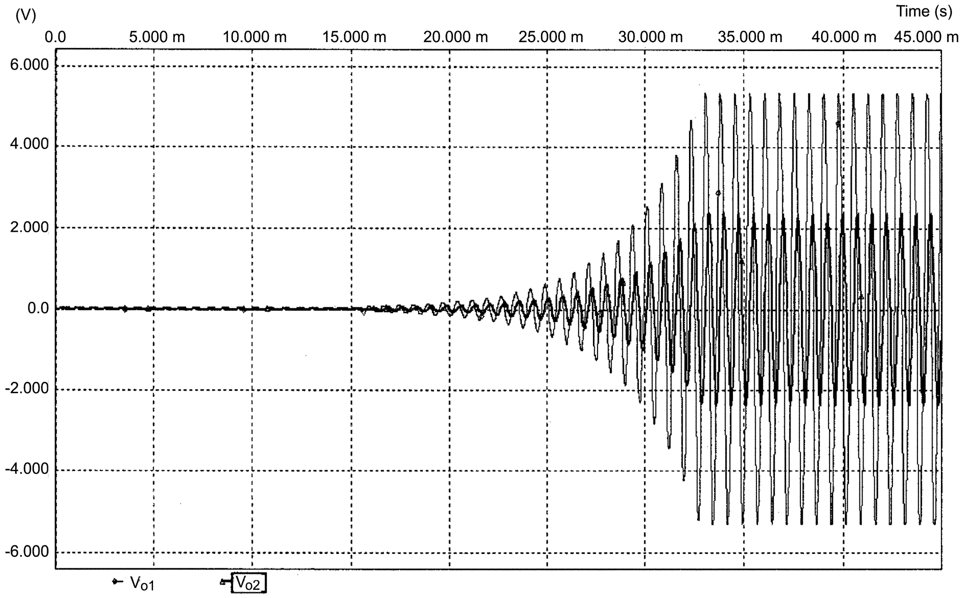

Fig. 4 — Growing oscillations of the quadrature voltage outputs

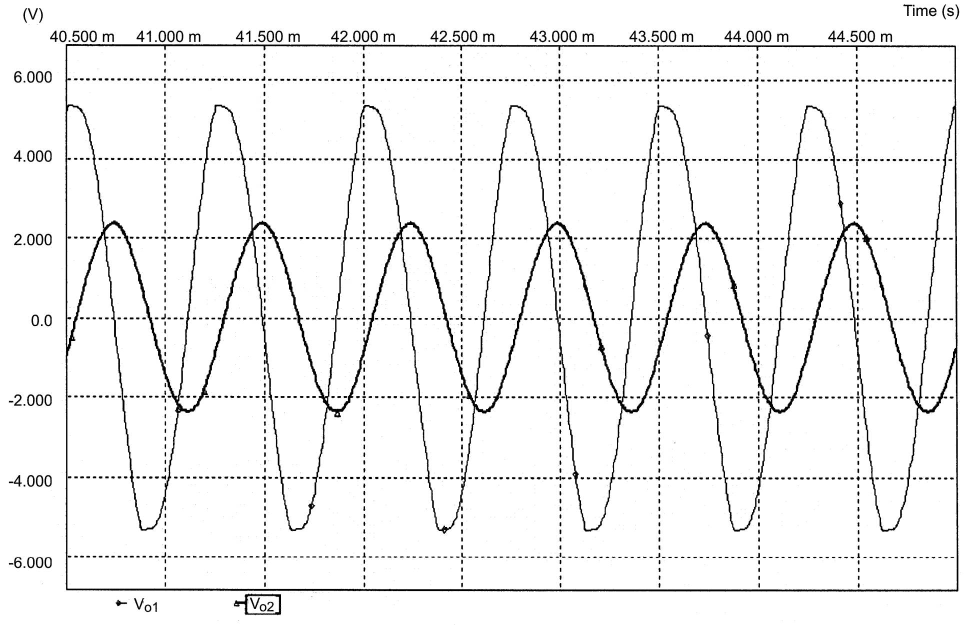

Fig. 5 — Steady state waveform of the quadrature voltage outputs

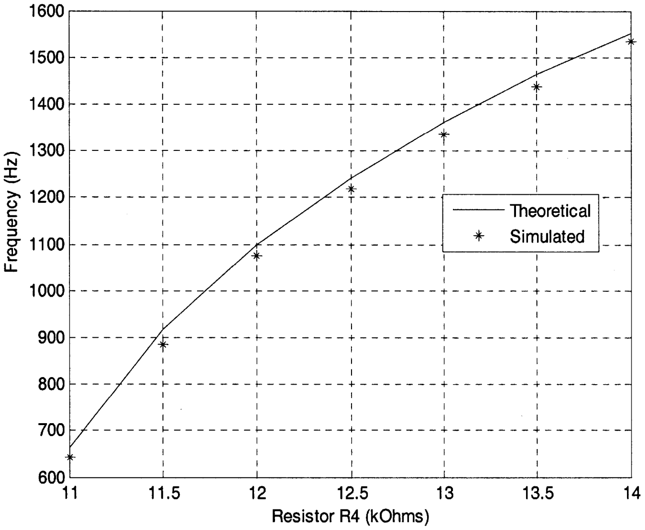

Fig. 6 — Theoretical and simulated results of the FO by varying resistor R_4

generated quadrature signals (V_{o2}/V_{o1}) is 0.44 which is also very close to the theoretical value of 0.4286 according to Eq. (8). Waveform for V_{o1} is −88.769° shifted with respect to V_{o2} as compared to the ideal value of −90°, i.e. quadrature error of 1.231°. It should also be noted that no auxiliary amplitude control circuitry has been used for limiting the amplitude. However, external amplitude limiter can be used to get the desired value of amplitudes with lower total harmonic distortion (THD) of the generated voltage signals. The variation of FO with resistor R_4 (as a single variable resistor) is shown in Fig. 6 and the simulated values are very close to the theoretical values.

6 Conclusions

Although several SRCO realizations using CDBA are reported in the literature, the realization of LFO using CDBA has not been investigated much. This paper presents novel LFOs which are created using two CDBAs, four/five resistors and two true/virtually grounded capacitors. The circuits provide two quadrature voltage outputs; enjoy the advantages of non-interactive control of the condition of oscillation (CO) and the frequency of oscillation (FO), suitability for monolithic integration and low incremental active and passive sensitivities. SPICE simulation results have verified the workability of the circuits.

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