An Efficient and Compact Mixed-Mode TOQO using Single CFDITA

Atul Kumar, Bhartendu Chaturvedi, and Shafali Jagga

Abstract—A novel electronically adjustable quadrature oscillator of third-order type is introduced in this paper. It is a mixed-mode oscillator as it generates two voltage and two current output signals. The proposed design uses a single current follower differential input transconductance amplifier along with three capacitors and two MOS-resistors. The use of all grounded capacitors makes it the best choice for modern integration technology. The paper includes detailed ideal, non-ideal and parasitic studies, frequency stability and phase noise analyses. In addition of simpler design and integration support, the proposed oscillator design has the features of good operational frequency (22.4 MHz), low total harmonic distortion (<1.7%), low operating supply voltages (±1 V) and low power consumption (0.14 mW). The theoretical aspects are validated by the post-layout simulation using gpdk 180 nm technology through Cadence Virtuoso tool. The layout of the used active device, current follower differential input transconductance amplifier occupies an area of 19 µm × 27 µm. Experimental verification using off-the-shelf ICs LM13700 and AD844 is also performed to check the practicality of the proposed design. The application perspective of the proposed third-order quadrature oscillator in terms of quadrature amplitude modulation (QAM) is also explored.

Index Terms—Analog Circuit, Quadrature Oscillator, Mixed-mode, QAM.

1. INTRODUCTION

Sinusoidal oscillator has emerged as an active block for generating sinusoidal signal(s) of uninterrupted and intended frequency. The oscillators do not require any input signal apart from providing the biasing. The oscillators perceive their applications in the field of communication system, instrumentation and measurement system, signal processing and control system [1-3]. Quadrature sinusoidal oscillators are more beneficial as they provide two or more output signals with 90° phase difference. The key features for the improved design of quadrature oscillator are to have minimum number of active and passive components, employment of grounded capacitors only, low harmonic distortion and availability of distinct outputs etc. However, it is well known fact that with the increase in the order of a network, performance parameters improve in terms of quality of waveform, accuracy, frequency response, and distortion. Eventually, third-order quadrature oscillators (QOs) discern higher frequency response, more accuracy, better quality factor, and lower value of distortion in comparison to the second-order counterparts. Subsequently, in the literature, a variety of third-order QOs has been revealed [4-24]. In [4], Roy and Pal designed QO using two voltage differencing current conveyors (VDCCs) along with six grounded passive components out of which three are capacitors and three are resistors. Chen et al. in [5] utilized two multiple output current controlled current conveyor transconductance amplifiers (MO-CCCCTAs) in combination with three grounded capacitors to realize a circuit of QO. Chen et al. in [6] presented QO using two multiple-output voltage differencing transconductance amplifiers (MO-VDTAs) alongside three grounded capacitors. Raj et al. reported a QO using three current feedback operational amplifiers (CFOAs) and eight passive components out of which three are grounded capacitors, three are grounded resistors and remaining two are floating resistors [7]. In [8], Mohan et al. reported a QO with two fully differential second-generation current conveyors (FDCCIIs), four MOS-based resistors, two floating and one grounded capacitor. Raj et al. presented a circuit of QO using four operational transconductance amplifiers (OTAs) and three grounded capacitors in [9]. Chen et al. reported third-order QO using two multiple output-differential voltage current conveyor transconductance amplifiers (MO-DVCCTAs) along with two grounded resistors and three grounded capacitors [10]. An improved design of resistorless QO is reported in [11] utilizing two VDTAs and three grounded capacitors. In [12], Ghosh et al. presented a QO circuit with two current differencing buffered amplifiers (CDBAs), four resistors and three capacitors. Nagar and Paul presented a QO in [13] that utilizes two operational transresistance amplifier (OTRAs), three capacitors and four resistors. Komal et al. in [14] reported a QO with three OTAs and three grounded capacitors. Pushkar and Bhaskar designed a QO circuit with two voltage differencing inverting buffered amplifiers (VDBIAS), one floating resistor and three grounded capacitors [15]. Nagar and Paul presented a QO utilizing two OTRAs, six floating passive components out of which three are capacitors and three are resistors [16]. An improved design of QO based on OTRA is presented in [17] wherein Chien realized a QO using single OTRA, three floating resistors, one floating and two grounded capacitors. In [18], Cicelki and Gokeen designed a QO circuit using three second generation current conveyors (CCIIIs), three grounded capacitors, and five MOS-based resistors. A resistorless version of the QO is also reported in [18]. In [19], Chaturvedi and Maheshwari reported a QO circuit with three differential voltage current conveyors (DVCCs), three grounded capacitors, two grounded resistors and one floating resistor. In [20], Maheshwari realized a QO circuit utilizing three voltage controlled differential voltage current conveyors (VC-DVCCs) combined with three grounded capacitors. In [21], Maheshwari and Verma presented a QO which employs four current controlled second generation conveyors (CCCIIs), three grounded capacitors and one grounded resistor. Maheshwari in [22] reported a resistorless design using three CCCIIs and three grounded capacitors.
capacitors. In [23], Shukla and Paul presented an oscillator based on single modified dual-X current controlled current conveyor transconductance amplifier (MDXCTA) and three grounded capacitors. The circuit is less complex and has very good operating frequency. Raj reported an oscillator with three CFOAs, three floating resistors, one floating and two grounded capacitors [24]. Earlier reported oscillators have one or more of the following shortcomings: (i) more than one ABB has been utilized in [4-16, 18-22, 24] that leads to design complexity and more power consumption (ii) more count of passive components [4, 7, 10, 12, 15-17, 19-21, 24] which increase the circuit complexity (iii) the operating frequency is less in the works of [5-8, 10-12, 14, 16-22, 24] (iv) use of floating passive components as in [7-8, 12, 13, 15-17, 19, 24] which provides less integration support (v) power consumption is high in [4, 6, 8-10, 13, 16-17, 23].

This work aims to overcome all the aforementioned limitations. For this purpose, a third-order QO using single current follower differential input transconductance amplifier (CFDITA), two MOS-resistors and three capacitors is presented in this paper. The proposed design does not use any floating passive component that leads to highly integrable design. Use of single active element makes the design simple and compact in size. Additionally, the proposed oscillator design has the features of low total harmonic distortion (THD), good operating frequency, low voltage and low power characteristics. The theoretical presumptions are validated using both simulations and experimental results.

II. NEWLY DESIGNED MIXED-MODE TOQO

The proposed third-order quadrature oscillator (TOQO) is based on CFDITA. The used device, CFDITA is an efficient current-mode active building block (ABB) that exhibits its electronic tunability [25-26]. It has been efficiently used in the design of various analog signal processing applications [27-32]. The proposed design of TOQO comprises of one CFDITA, two MOS-resistors and three grounded capacitors as depicted in Fig. 1(a). MOS transistors $M_{R1}$ and $M_{R2}$ are used to implement the active resistor $R_{M1}$ and $R_{M2}$ respectively. The use of all grounded capacitors helps in integration support. The terminal's voltages and currents of CFDITA are portrayed as follows.

$$I_Z = I_F, \quad I_O = g_m(V_Z - V_F); \quad g_m = \sqrt{k_m I_B} \quad (1)$$

where, $I_Z$, $I_F$ and $I_O$ are the currents at Z, F and O terminals respectively; $V_Z$ and $V_F$ are the voltages at Z and V terminals respectively; $g_m$ is the transconductance of CFDITA which is controllable via bias current $I_B$. In (1), $k_m = \mu_C AVL$, is the physical parameter of MOS transistor.

The design flow of the proposed TOQO is given in Fig. 1(b). A second-order low-pass filter (LPF) is cascaded with an inverting integrator to realize the proposed TOQO. The active resistors $R_{M1}$ and $R_{M2}$ along with capacitors $C_1$ and $C_3$ form a second-order LPF with input voltage at Z terminal. The capacitor $C_2$ forms an inverting integrator.

$$V_2 = -j\omega R_{M2} C_2 I_1, \quad I_2 = -j\omega R_{M2} C_3 I_1 \quad (7)$$

Fig. 1. (a) Newly designed mixed-mode TOQO (b) Design flow of the proposed TOQO

Characteristic equation (CE) derived after analyzing the circuit of Fig. 1 is expressed as follows.

$$s^3 R_{M1} R_{M2} C_1 C_2 C_3 + s^2 C_2 (R_{M1} C_1 + R_{M2} C_1 + R_{M2} C_3) + s C_2 + g_m = 0 \quad (2)$$

Frequency of oscillation (FO), $\omega_0$ is expressed as follows.

$$\omega_0 = \frac{1}{\sqrt{R_{M1} R_{M2} C_1 C_3}} \quad (3)$$

Condition of oscillation (CO) is given as follows.

$$R_{M1} R_{M2} C_1 C_3 g_m = C_2 (R_{M1} C_1 + R_{M2} C_1 + R_{M2} C_3) \quad (4)$$

If $R_{M1} = R_{M2} = R_M$ and $C_1 = C_2 = C_3 = C$ then FO and CO are expressed as given below.

$$\text{FO: } \omega_0 = \frac{1}{R_M C} \quad (5)$$

$$\text{CO: } g_m = \frac{3}{R_M} \quad (6)$$

It is observed that for a fixed value of $R_M$, CO can be controlled independently via transconductance, $g_m$. The FO can be independently controlled by varying the capacitor value.

The proposed design provides two voltages and two current outputs which are in quadrature relation with each other. The quadrature relationships between the two voltages and two currents are expressed below in (7).
III. NON-IDEAL AND PARASITIC STUDIES

A. Non-ideal Study

The non-idealities of active device, CFDITA are represented as given in (8).

\[ I_Z = aI_F \text{ and } I_O = g_m (V_Z - V_y) \]  \tag{8}

where \( a \) is the non-ideal current gain and \( \gamma \) is the non-ideal transconductance gain. The modified CE, considering the non-idealities, is expressed as follows.

\[
s^3R_{M1}R_{M2}C_1C_3 + s^2R_{M1}C_3 + s^2R_{M2}C_2C_3 + s^2C_2 + sC_2 + a\gamma g_m = 0
\]  \tag{9}

The obtained FO, \( \omega_0 \) is expressed as follows.

\[ \omega_0 = \frac{1}{\sqrt{R_{M1}R_{M2}C_3}} \]  \tag{10}

The modified CO obtained from (8) is given as follows.

\[ R_{M1}R_{M2}C_3a\gamma g_m = C_2(R_{M1}C_1 + R_{M2}C_1 + R_{M2}C_3) \]  \tag{11}

Assuming \( R_{M1} = R_{M2} = R_M, C_1 = C_2 = C_3 = C \), FO and CO can be expressed as followed in (12) and (13) respectively.

\[ \text{FO: } \omega_0 = \frac{1}{R_MC} \]  \tag{12}

\[ \text{CO: } g_m = \frac{3}{a\gamma R_M} \]  \tag{13}

B. Parasitic Study

The terminals Z, V and O of the CFDITA are of high impedance while terminal F is of low impedance. The parasitic involved in CFDITA at F terminal is a series resistance \( R_F \). At terminals, Z, V, and O, parasitic impedance \( R_Z \) in parallel with \( (1/sC_2) \), \( R_T \) in parallel with \( (1/sC_3) \) and \( R_O \) in parallel with \( (1/sC_3) \) appear respectively. After considering the parasitic of CFDITA, the modified CE is given as follows:

\[
s^3R_{M1}R_{M2}'C_1'C_3 + s^2C_1'(R_{M1}C_1' + R_{M2}'C_1' + R_{M2}C_3) + s^2C_2' + g_m = 0
\]  \tag{14}

where, \( R_{M2}' = R_{M2} + R_F \), \( C_1' = C_1 + C_O \), and \( C_2' = C_2 + C_Z \).

The modified FO, \( \omega_0 \) including parasitic is expressed as follows.

\[ \omega_0 = \frac{1}{\sqrt{R_{M1}R_{M2}'C_1'C_3}} \]  \tag{15}

It is observed from (15) that the proposed oscillator design is less affected by the parasitic of CFDITA as the parasitic of CFDITA are absorbed by external resistor and capacitor.

IV. FREQUENCY STABILITY AND PHASE NOISE ANALYSES

A. Frequency Stability Analysis

Frequency stability determines the ability of how long the frequency remains constant with respect to time. Frequency stability factor (\( S_F \)) [33] can be expressed as in (16) as follows.

\[ S_F = \left. \frac{d\phi(u)}{du} \right|_{u=1} \]  \tag{16}

In (16), \( u = \omega/\omega_0 \). is the normalized frequency here and \( \phi(u) \) is the phase function of the oscillator’s open loop transfer function. The open loop transfer function of the proposed QO is given as follows.

\[ H(s) = \frac{-g_m}{D(s)} \]  \tag{17}

where, \( D(s) = s^3R_{M1}R_{M2}C_1C_3 + s^2R_{M1}C_3 \) \( + s^2R_{M2}C_2 + s^2R_{M2}C_3 + sC_2 \)

Let \( R_{M1} = R_{M2} = R_M \) and \( C_1 = C_2 = C_3 = C \). The open loop transfer function in (17) can now be written as follows.

\[ H(u) = \frac{3}{u^2(2n + 1) + ju(u^2 - 1)\sqrt{n}} \]  \tag{18}

The phase function \( \phi(u) \) can be calculated as

\[ \phi(u) = -\tan^{-1}\left(\frac{u(u^2 - 1)\sqrt{n}}{u(2n + 1)}\right) \]  \tag{19}

Furthermore, \( S_F \) can be computed as given in (20).

\[ S_F = \left. \frac{d\phi(u)}{du} \right|_{u=1} = \frac{2\sqrt{n}}{2n + 1} \]  \tag{20}

It is clearly interpreted from (19) that \( S_F \) is independent of \( \omega_0 \). So, it may be concluded that the proposed TOQO has good frequency stability.

B. Phase Noise Analysis

To analyze the phase noise, oscillator is treated as a feedback system as shown in Fig. 2 in which each source of noise that can be the thermal noise of active or passive elements, noise due to supply and substrate, and low frequency noise of MOS devices, is taken as input. The phase noise at the output is observed as a function of all sources of noise present at the input and the extent of rejection of noise by the feedback system.

Phase noise power spectral density in a linear oscillator system is modeled by the following relationship [34].

\[ \left[ \frac{Y}{X} \right]^{-2} = \frac{1}{(\Delta\omega)^2} \left| \frac{dH}{d\omega} \right|^2 \]  \tag{21}
where $\omega_0$ is FO and $\omega = \omega_0 + \Delta \omega$ is the frequency close to carrier frequency. To get more insight to it, assume $H(j\omega) = A(\omega) \exp[j \varphi(\omega)]$, then

$$\frac{dH}{d\omega} = \left(\frac{dA}{d\omega} + j A \frac{d \varphi}{d\omega}\right) \exp[j \varphi(\omega)].$$

Under the condition, $\omega \approx \omega_0$ and $A \approx 1$, (21) can be written as follows.

$$\left[\frac{Y}{X}[j(\omega_0 + \Delta \omega)]\right]^2 = \frac{1}{(\Delta \omega)^2 \left[\left(\frac{dA}{d\omega}\right)^2 + \left(\frac{d \varphi}{d\omega}\right)^2\right]}.$$ (22)

As already stated the open loop transfer function of the proposed oscillator in (17), the same can be represented in terms of $\omega$ as follows.

$$H(j\omega) = \frac{g_m}{D(s)}$$

where

$$D(s) = \omega_0^2 C_2 (R_{M1} C_1 + R_{M2} C_1 + R_{M2} C_3) + j C_2 \omega_0^2 R_{M1} R_{M2} C_1 C_3 - \omega_0.$$ 

The terms $A(\omega)$ and $\varphi(\omega)$ can be found from (22) as given ahead.

$$\left|\frac{dA(\omega)}{d\omega}\right| = \frac{2}{\omega_0} \quad \text{and} \quad \left|\frac{d \varphi(\omega)}{d\omega}\right| = \frac{2}{3\omega_0}.$$ (24)

From (22) and (24), it is observed that noise power spectral density is a function of $\omega_0$.

\[ \text{Fig. 2. Linear oscillator system} \]

\[ \text{V. SIMULATION RESULTS AND DISCUSSION} \]

Post-layout simulations are carried out through 180 nm gpdk technology using Cadence Virtuoso tool to verify the proposed TOQO. The CMOS implementation and layout of the used device, CFDITA are illustrated in Fig. 3. It measures 19 µm × 27 µm in size. The power supplies and bias voltage of ±1 V and $V_{B1} = -0.55$ V respectively are used in simulations. Aspect ratios, W (µm)/L (µm) of the MOSFETs incorporated in the CMOS implementation of CFDITA are given as follows: $M_{1,2} = 0.4/0.18, M_{3,4} = 1.44/0.18, M_{5,6} = 3.6/0.18, M_{7,8,9} = 16.2/0.18, M_{10,11} = 9/0.18, M_{12,13} = 1/0.18, \text{and } M_{14} = 3.6/0.36$. Capacitors $C_1, C_2, \text{and } C_3$ are chosen with the value of 10 pF. The control voltages $V_{C1}$ and $V_{C2}$ are set to 0.71 V to yield resistances, $R_{M1} = R_{M2} = 5 \text{ k} \Omega$. A bias voltage of $V_{B2} = -0.22$ V is used to generate a bias current of 90 µA to yield the transconductance, $g_m = 0.6$ mS. Time domain responses of the two output voltages, $V_1$ and $V_2$, in steady state are depicted in Fig. 4.

Fast Fourier Transform (FFT) responses of output voltages, $V_1$ and $V_2$, are depicted in Fig. 5. The time domain responses of output currents, $I_1$ and $I_2$, are depicted in Fig. 6 and their FFT responses are delineated in Fig. 7. The oscillation frequency obtained is 3.31 MHz. At this frequency, THD for the voltage outputs is found within 1.5% and for the current outputs is found within 1.7%. The proposed circuit consumes power of 0.14 mW only.

\[ \text{Fig. 3. (a) CMOS implementation of CFDITA (b) Layout of CFDITA} \]

\[ \text{Fig. 4. Time domain responses of output voltages in steady state at 3.31 MHz} \]
The performance of the proposed circuit against process variation and MOS transistors mismatch is examined using Monte Carlo simulation (MCS) analysis. A total of 100 runs of MCS with random sampling are carried out. Fig. 8 and Fig. 9 depict MCS results as histogram of oscillation frequency for process variation and MOS transistors mismatch respectively which confirm that the proposed QO has good performance against process variation and MOS transistors mismatch. The output responses of the proposed QO at high frequency are also examined by changing the capacitor values to 1.5 pF. The transient responses of voltages, \( V_1, V_2 \) and currents, \( I_1, I_2 \) at 22.4 MHz are illustrated in Fig. 10. Additionally, the variation of frequency against the capacitor value is shown in Fig. 11. The frequency varies from 0.85 MHz to 22.4 MHz when capacitor value is varied from 40 pF to 1.5 pF. A comparison of the performance features of the proposed TOQO with relevant state-of-the-art works is given in Table 1.
Table 1: Comparison of the proposed TOQO with relevant state-of-the-art works

<table>
<thead>
<tr>
<th>Ref.</th>
<th>ABB/count</th>
<th>No. of external resistors F/G</th>
<th>No. of capacitors F/G</th>
<th>THD</th>
<th>No. of current outputs</th>
<th>No. of voltage outputs</th>
<th>Maximum Operating frequency</th>
<th>Technology (µm)</th>
<th>Supply voltages (V)</th>
<th>Power consumption (mW)</th>
</tr>
</thead>
<tbody>
<tr>
<td>[4]</td>
<td>VDCC/2</td>
<td>3G</td>
<td>3G</td>
<td>1.89%</td>
<td>3</td>
<td>2</td>
<td>20.87 MHz</td>
<td>0.18</td>
<td>±0.9</td>
<td>1.28</td>
</tr>
<tr>
<td>[5]</td>
<td>CCCCTA/2</td>
<td>0</td>
<td>3G</td>
<td>&lt;2%</td>
<td>3</td>
<td>2</td>
<td>2.11 MHz</td>
<td>0.18</td>
<td>±0.9</td>
<td>--</td>
</tr>
<tr>
<td>[6]</td>
<td>VDTA/2</td>
<td>2F/3G</td>
<td>3G</td>
<td>0.33%</td>
<td>0</td>
<td>3</td>
<td>2.12 Hz</td>
<td>--</td>
<td>±10*</td>
<td>--</td>
</tr>
<tr>
<td>[7]</td>
<td>CFOA/3</td>
<td>2F</td>
<td>3G</td>
<td>3G</td>
<td>3G</td>
<td>3</td>
<td>2.15 MHz</td>
<td>0.18</td>
<td>±1.25</td>
<td>2.6</td>
</tr>
<tr>
<td>[8]</td>
<td>FDCCII/2</td>
<td>0</td>
<td>2F+1G</td>
<td>&lt;3%</td>
<td>2</td>
<td>2</td>
<td>1.56 MHz</td>
<td>0.18</td>
<td>±0.9</td>
<td>--</td>
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<tr>
<td>[9]</td>
<td>OTA/4</td>
<td>3G</td>
<td>&lt;1.13%</td>
<td>2</td>
<td>3</td>
<td>15.64 MHz</td>
<td>1.28</td>
<td>0.18</td>
<td>±0.9</td>
<td>--</td>
</tr>
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<td>[10]</td>
<td>DVCCCTA/2</td>
<td>2G</td>
<td>3G</td>
<td>&lt;1.3%</td>
<td>3</td>
<td>2</td>
<td>2.11 MHz</td>
<td>0.18</td>
<td>±0.9</td>
<td>1028</td>
</tr>
<tr>
<td>[11]</td>
<td>VDTA/2</td>
<td>0</td>
<td>3G</td>
<td>&lt;4.5%</td>
<td>3</td>
<td>3</td>
<td>3.17 MHz</td>
<td>0.18</td>
<td>±0.9</td>
<td>--</td>
</tr>
<tr>
<td>[12]</td>
<td>CDFA/2</td>
<td>3F/1G</td>
<td>1F+2G</td>
<td>2.46%</td>
<td>2</td>
<td>0</td>
<td>75 kHz</td>
<td>0.18</td>
<td>±0.9</td>
<td>--</td>
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<td>[13]</td>
<td>OTRA/2</td>
<td>0</td>
<td>3F</td>
<td>1.83%</td>
<td>2</td>
<td>0</td>
<td>18.58 MHz</td>
<td>0.5</td>
<td>±1.5</td>
<td>1.622</td>
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<td>[14]</td>
<td>OTA/3</td>
<td>0</td>
<td>3G</td>
<td>&lt;0.49%</td>
<td>2</td>
<td>0</td>
<td>32.98 MHz</td>
<td>0.18</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>[15]</td>
<td>VDBA/2</td>
<td>1F</td>
<td>3G</td>
<td>--</td>
<td>2</td>
<td>0</td>
<td>--</td>
<td>0.18</td>
<td>±0.9</td>
<td>--</td>
</tr>
<tr>
<td>[16]</td>
<td>OTRA/2</td>
<td>3F</td>
<td>3F</td>
<td>1.17%</td>
<td>2</td>
<td>0</td>
<td>29.04 kHz</td>
<td>0.5</td>
<td>±1.5</td>
<td>1.522</td>
</tr>
<tr>
<td>[17]</td>
<td>OTRA/1</td>
<td>3F</td>
<td>1F+2G</td>
<td>1.90%</td>
<td>1</td>
<td>0</td>
<td>1.08 MHz</td>
<td>0.35</td>
<td>±2.5</td>
<td>6.8</td>
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<tr>
<td>[18]</td>
<td>CCII/3,</td>
<td>0</td>
<td>3G</td>
<td>&lt;2.94%</td>
<td>2</td>
<td>2</td>
<td>3.24 MHz</td>
<td>0.18</td>
<td>±0.9</td>
<td>--</td>
</tr>
<tr>
<td>[19]</td>
<td>DVCC/3</td>
<td>1F</td>
<td>2G</td>
<td>&lt;1.82%</td>
<td>4</td>
<td>2</td>
<td>7.94 MHz</td>
<td>0.5</td>
<td>±2.5</td>
<td>--</td>
</tr>
<tr>
<td>[20]</td>
<td>VC-DVCC/3</td>
<td>3G</td>
<td>3G</td>
<td>&lt;1%</td>
<td>2</td>
<td>3</td>
<td>795 kHz</td>
<td>0.5</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>[21]</td>
<td>CCCII/4</td>
<td>1G</td>
<td>3G</td>
<td>&lt;2%</td>
<td>4</td>
<td>2</td>
<td>9.78 MHz</td>
<td>0.25</td>
<td>±2.5</td>
<td>--</td>
</tr>
<tr>
<td>[22]</td>
<td>CCCII/3</td>
<td>0</td>
<td>3G</td>
<td>&lt;2%</td>
<td>4</td>
<td>2</td>
<td>4 MHz</td>
<td>0.5</td>
<td>±2.5</td>
<td>--</td>
</tr>
<tr>
<td>[23]</td>
<td>MDXCTA/1</td>
<td>0</td>
<td>3G</td>
<td>&lt;0.84%</td>
<td>3</td>
<td>2</td>
<td>52.94 MHz</td>
<td>0.18</td>
<td>±1</td>
<td>1.08</td>
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<td>[24]</td>
<td>CFOA/3</td>
<td>3F</td>
<td>2G+1F</td>
<td>0.23%</td>
<td>0</td>
<td>3</td>
<td>0.4 MHz</td>
<td>--</td>
<td>±8</td>
<td>1.522</td>
</tr>
<tr>
<td>This work</td>
<td>CFDITA/1</td>
<td>0</td>
<td>3G</td>
<td>&lt;1.7%</td>
<td>2</td>
<td>2</td>
<td>22.4 MHz</td>
<td>0.18</td>
<td>±1</td>
<td>0.14</td>
</tr>
</tbody>
</table>

*: data not available, * indicates experimental measurements.

VI. APPLICATION ASPECT

Quadrature sinusoidal oscillators discern applications in the field of communication as analogue and digital modulation/demodulation techniques of quadrature amplitude modulation (QAM) and quadrature phase shift keying (QPSK). To validate this application aspect of the newly designed TOQO, QAM process is presented in Fig. 12. In Fig. 12 (a), QAM transmitter modulates two distinct input message signals \( m_1(t) \) and \( m_2(t) \), with two respective carrier signals \( x_1\cos(\omega t) \) and \( x_2\sin(\omega t) \) generated by the proposed QO. Both the carrier signals have same bandwidth but are in quadrature relation with each other. The transmitted output signal, \( s(t) \) generated by the QAM transmitter is given by \( s(t) = m_1(t)x_1\cos(\omega t)+m_2(t)x_2\sin(\omega t) \). The output transmitted by QAM transmitter is fed as an input to QAM receiver. In Fig. 12 (b), QAM receiver demodulates the received signal \( s(t) \) to generate the two distinct message signals \( m'_1(t) \) and \( m'_2(t) \). The demodulation process is carried out with the utilization of the same carrier signals originated from the proposed QO, which are used in the modulation process.

Fig. 13 shows the two input message signals \( m_1(t) \) and \( m_2(t) \) with amplitude 1 V and frequency 2 kHz and 4 kHz respectively. Fig. 14 shows the modulated output signal \( s(t) \) generated by QAM transmitter. Fig. 15 illustrates the two demodulated signals \( m'_1(t) \) and \( m'_2(t) \) generated by QAM receiver. It is clearly seen from Fig. 15 that demodulated signals \( m'_1(t) \) and \( m'_2(t) \) at the output of QAM receiver have the frequencies similar to the input message signals \( m_1(t) \) and \( m_2(t) \), respectively.

![Frequency variation with respect to change in capacitor value](image)

Fig. 11. Frequency variation with respect to change in capacitor value
VII. EXPERIMENTAL VERIFICATION

The proposed TOQO has also been verified experimentally. Fig. 16 illustrates the hardware implementation of the used device, CFDITA connecting off-the-shelf ICs AD844 and LM13700 along with the practical implementation of a current source to provide bias current to IC LM13700. A bias voltage of $V_B = 0.2$ V and a resistor of $R = 10$ kΩ are used to generate a bias current of $I_B = 20 \mu A$ which yields a transconductance, $g_m$, of $0.3$ mS. The resistances values are chosen as $10$ kΩ and capacitance values as $10$ nF to generate $1.57$ kHz output frequency signal. The observed time domain waveforms for voltages, $V_1$ and $V_2$ and Lissajous pattern between them are depicted in Fig. 17. The circuit is also experimentally verified for various values of $R$ and $C$ to generate output signals of different frequencies. Fig. 18 reveals the time domain output voltage signals, $V_1$ and $V_2$ at $16.4$ kHz when $R = 10$ kΩ and $C = 1$ nF. Fig. 19 reveals the
time domain output voltage signals, $V_1$ and $V_2$ at 187 kHz when $R = 1$ kΩ and $C = 1$ nF.

Fig. 16. (a) Hardware Implementation of CFDITA (b) Practical implementation of current source to provide bias current to IC LM13700

Fig. 17. (a) Time domain output voltage signals at 1.57 kHz (b) Lissajous pattern

Fig. 18. Time domain output voltage signals at 16.4 kHz

Fig. 19. Time domain output voltage signals at 187 kHz

VIII. CONCLUSION

In this work, an efficient and compact TOQO is proposed that utilizes single CFDITA, two MOS resistors and three grounded capacitors for generating two voltage and two current output signals. The reported circuit fulfills the requirement for IC technology as it makes use of grounded capacitors and MOS transistors only. The suggested design is electronically tunable via control voltage and has power consumption of 0.14 mW. The detailed non-ideal study, parasitic study, frequency stability and phase noise analyses of the proposed oscillator are included in the paper. Post-layout simulations based on 180 nm gpdk technology using Cadence Virtuoso tool have been performed and results confirm the theoretical analyses. Experimental verification has also been performed to validate the practicality of proposed structure. Application aspect of the proposed TOQO in terms of QAM transmitter and receiver is also explored.

REFERENCES


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