Programmable Universal Filter and Quadrature Oscillator Using Single Output Operational Transconductance Amplifiers

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Abstract: This paper presents a new programmable universal filter and quadrature oscillator based on the single output operational transconductance amplifiers (OTAs). The proposed universal filter and quadrature oscillator can be achieved into single topology by programming analog switches. When the circuit performs as a universal filter, it can realize low-pass, high-pass, band-pass, band-stop and all-pass filters with orthogonal and electronic controls of the natural frequency and quality factor. When the circuit performs as a quadrature oscillator, it provides a three-phase quadrature output signal which the condition and frequency of oscillations can be controlled orthogonally and electronically. The proposed structure can be realized based on the single output OTAs which are easily implemented as both commercially available integrated circuits (ICs) as OTAs and complementary metal-oxide semiconductor (CMOS) OTAs as IC forms. SPICE simulation using standard 0.18 µm CMOS process is used for investigating the performance of the proposed circuit whereas the workability of new circuit is confirmed by LM13600 discrete-component integrated circuits as OTAs.

Keywords: Universal filter; quadrature oscillator; operational transconductance amplifier; analog signal processing; voltage-mode circuit

Programirljiv univerzalni filter in kvadraturni oscillator z uporabo enojnih izhodnih operacijskih transkonduktančnih ojačevalnikov

Izvleček: Članek predstavlja nov programirljiv univerzalni filter in kvadraturni oscillator, ki temelji na enojnih izhodnih operacijskih transkonduktančnih ojačevalnikih (OTA). Predlagani univerzalni filter in kvadraturni oscillator je mogoče s programiranjem analognih stikal združiti v enotno topologijo. Ko veze deluje kot univerzalni filter, lahko izvede nizkoprepustne, visokoprepustne, pasovne, zaporne in vseprepustne filtre z ortogonalnim in elektronskim upravljanjem lastne frekvence in faktorja kakovosti. Če veze deluje kot kvadraturni oscillator, zagotavlja trifazni kvadraturni izhodni signal, katerega stanje in frekvenco oscilacij je mogoče ortogonalno in elektronsko krmiliti. Predlagano strukturo je mogoče realizirati na podlagi enojnih izhodnih OTAs, ki jih je mogoče enostavno izvesti tako v obliki komercialno dostopnih integriranih vezij (IC) kot OTA kot komplementarnih kovinsko oksidnih polprevodniških (CMOS) OTAs v obliki IC. Simulacija SPICE z uporabo standardnega 0,18 µm CMOS procesa je uporabljena za raziskovanje delovanja predlaganega vezja, medtem ko je uporabnost novega vezja potrjena z diskretnimi integriranimi vezji LM13600 kot OTA.

Ključne besede: Univerzalni filter; kvadraturni oscillator; operacijski transkonduktančni ojačevalnik; analogna obdelava signalov; napetostno vezje

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How to cite: B. Knobnob et al., “Programmable universal filter and quadrature oscillator using single output operational transconductance amplifiers”, Inf. Midem-J. Microelectron. Electron. Compon. Mater., Vol. 51, No. 4(2021), pp. 225–241

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1 Introduction

The operational transconductance amplifiers (OTAs) are commonly used to realize analog signal processing circuits [1], [2]. There are numerous advantages of using OTA such as electronic tuning capability, simple structure, easy for implementing both bipolar junction transistor (BJT) and complementary metal oxide semiconductor (CMOS) with the same structure and powerful ability to generate various circuits. The OTA based circuits require no resistors therefore making it suitable for integrated circuits (ICs) implementation. There are discrete-component ICs as OTAs such as CA3080, LM13600, LM13700, NE5517 and MAX435 commercially available. It should be noted that discrete-component ICs as OTAs are single output devices therefore the utilization of single output OTA based circuits is very crucial. Although numerous outputs can be obtained by connecting the input terminals in parallel, using discrete component ICs, the number of devices utilized will equal the number of required outputs, increasing the component count and power consumption.

The universal biquad filters are the topologies that usually provide variant second-order filtering responses from the same topology including low-pass (LP), band-pass (BP), high-pass (HP), band-stop (BS) and all-pass (AP). This filter can be applied to electronic, control and communication systems such as cross-over network used in a three-way high-fidelity loudspeaker, touch-tone telephone used for tone decoders and phase-locked loop used for FM stereo demodulators [3]. Additionally, it can also be used as a subcircuit for realizing high-order filters [4]. Many universal biquad filters have been reported, for example, see [5]-[28]. OTA-based universal filters have been proposed already in [9]-[28]. Considering input and output terminals, these universal filters can be classified into three categories: (i) single-input multiple-output (SIMO) filter [9], [10], (ii) multiple-input single-output (MISO) filter [11]-[22] and (iii) multiple-input multiple-output (MIMO) filter [23]-[28]. The SIMO filter provides variant filtering responses for the output terminals of LP, BP, HP, BS, and AP when a single input signal is applied. The MISO filter delivers variant filtering responses by appropriately applying the input signal and output signal can be obtained with single output terminal while MIMO filter provides filtering responses by appropriately applying the input signals and appropriately selecting the output terminals. Compared to the SIMO filter, the MISO and MIMO filters usually require lesser active and passive elements. The voltage-mode universal filters typically require the properties such as high-input and low-output impedances to obviate additional buffer circuits, absent from inverting-type input signal requirements to avoid additional inverting amplifiers and orthogonal controls of the natural frequency and quality factor.

Quadrature oscillators are the circuits that usually provide two sinusoids with 90° phase difference for a variety of applications such as for telecommunications in quadrature mixers, single-sideband generators, direct-conversion receivers or for measurement purposes in vector-generators and phase sensitive detection [29], [30]. Several quadrature oscillators have been reported, for example, see [30]-[36]. Quadrature oscillators that enjoy orthogonal control of the condition and frequency of oscillations are required. OTA-based quadrature oscillators have been proposed, for example, see [37]-[39].

Recently, the structures that can give both universal filter and quadrature oscillator have been reported [40]-[57]. The universal filter and quadrature oscillator can be obtained with the same topology [40]-[49] however, it is necessary to change the connection for obtaining either a universal filter or a quadrature oscillator. Furthermore, several of these topologies suffer from some drawbacks such as exciting the input signal through capacitors [40], [41], requiring component-matching condition for obtaining all-pass filtering responses [42], [45], [47], [48], requiring minus-type input signal or double input signal for obtaining some filtering responses [43], lacking orthogonal control of the natural frequency and the quality factor [44] and obtaining the current output that flowing through capacitor which is not ideal for integrated circuits implementation [49].

The structure in [50] realizes universal filter and quadrature oscillator without changing any connection, but only LP, HP and BP filters are provided. The structure in [51] realizes quadrature oscillator and its structure can be modified to work as universal filter, but only LP and BP filtering responses are obtained. The structures in [52]-[57] realize universal filter and quadrature oscillator without changing any connection. In [52]-[53], either a universal filter or a quadrature oscillator can be obtained by selecting the switches, but passive-matching condition is required for obtaining HP filtering response. In [54], the universal filter or the quadrature oscillator can be obtained by adjusting the ratio of resistances while in [55]-[57], the universal filter or the quadrature oscillator can be obtained by adjusting the ratio of bias currents. It is well-known that the filters are commonly realized based on linear system whereas oscillators are generally realized based on non-linear system. As a result, the condition for obtaining universal filter and quadrature oscillator by adjusting the ratio of resistances [54] and the ratio of bias currents [55]-[57] must be careful. Especially, in case of the circuits
are operated as high-Q filters, self-oscillation must be avoided.

OTA-based universal filter and quadrature have been already reported [18], [25]-[28], but these systems provide universal filter and quadrature oscillator by adding or modifying the feedback connection.

This work proposes a new programmable voltage-mode universal filter and three-phase quadrature oscillator using single output OTAs and grounded capacitors. Universal filter and quadrature oscillator can be achieved into single topology by programming using analog switches. If the circuit acts as universal filter, it is a four-input one-output universal filter that offers the advantages such as realizing LP, BP, HP, BS, and AP filters by appropriately applying input signal, without inverting-type signal requirements and high-input impedance. The natural frequency and quality factor can also be controlled orthogonally and electronically. In case the circuit works as quadrature oscillator, it is a three-phase quadrature oscillator that the condition and frequency of oscillation can be controlled orthogonally and electronically. For IC implementation, the usage of grounded capacitor is ideal and the use of single-output OTAs is also easily implemented as commercially integrated circuits (ICs). SPICE simulation results using standard 0.18 µm CMOS technology are used to verify the characteristic of the proposed circuit. The results of an experiment are used to confirm the workability of the new topology.

The comparison of the proposed circuit with those of previous universal filters and quadrature oscillators is shown in Table 1. Compared with the circuits in [53]-[54], the proposed circuit offers electronic controls, without component-matching condition, high input impedance and using ground capacitor. Compared with the current-mode circuits in [55]-[57], the proposed circuit offers a new technique for obtaining universal filter and quadrature oscillator. Namely the programmable technique which can be easy obtained universal filter or quadrature oscillator. If focusing only universal filter, the comparison of the proposed circuit with some universal filters is shown in Table 2. Comparing with voltage-mode universal filters in [20], [21], the proposed filter does not require component-matching condition or inverting-type input signal for obtaining five filtering responses. Compared with the current-mode universal filters in [46], [47], the proposed filter is absent from passive resistors.

### 2 Proposed circuit

The circuit symbol of OTA is shown in Fig. 1 and its ideal characteristic can be described by

\[ I_o = g_m (V_{in+} - V_{in-}) \]  

(1)

where \( I_o \) is the output current, \( g_m \) is the transconductance gain, \( V_{in+} \) and \( V_{in-} \) denote respectively non-inverting and inverting input terminals.

### Table 1: Comparison of this work with those of previous universal filter and quadrature oscillator.

| Factor | [53] | [54] | [55] | [56] | [57] | Fig. 4 |
|--------|------|------|------|------|------|--------|
| Number of active devices | 2-DVCC | 2-CFA | 3-CFTA | 2-CCCI | 2-CCFTA | 5-OTA |
| Number passive components | 2-C, 2R | 2-C, 3-R | 2-C, 1-R | 2-C | 2-C | 2-C |
| Operation mode | CM | VM | CM | CM | CM | VM |
| Using grounded capacitor | Yes | No | Yes | Yes | Yes | Yes |
| Offer universal filter/quadrature oscillator into single topology | Yes | Yes | Yes | Yes | Yes | Yes |
| Technique to obtaining filter/oscillator | SW | Con | Con | Con | Con | Pro |
| Independent control of \( \omega_o \) and \( Q \) of filter | Yes | No | Yes | Yes | Yes | Yes |
| No component-matching condition for obtaining five responses | No | No | Yes | Yes | Yes | Yes |
| Independent control of CO and FO of oscillator | Yes | No | Yes | Yes | Yes | Yes |
| Offer electronic controls | Yes | No | Yes | Yes | Yes | Yes |
| Obtaining results | Sim/Exp | Sim | Sim | Sim/Exp | Sim | Sim/Exp |

**Note:** CFA = current feedback amplifier, CFTA = current follower transconductance amplifier, CCCII = current controlled second-generation current conveyor, CCFTA = current controlled current follower transconductance amplifier, VM = voltage-mode, CM = current-mode, SW = using switch, Con = using condition, Pro = using programmable, Sim = simulation, Exp = experimental
Table 2: Comparison of this work with those of previous universal filters.

| Factor                                      | [20]  | [21]  | [26]  | [47]  | [49]  | Fig. 2 |
|---------------------------------------------|-------|-------|-------|-------|-------|--------|
| Number of active devices                    | 5-OTA | 5-OTA | 5-OTA | 2-VDCC| 1-VDGA| 5-OTA |
| Number passive component                    | 2-C   | 2-C   | 2-C   | 2-C & 2-R | 2-C & 2-R | 2-C |
| Type of filter                              | MISO  | MISO  | MISO  | SIMO  | SIMO  | MISO  |
| Independent control of $\omega_o$ and Q of filter | Yes   | No    | Yes   | Yes   | Yes   | Yes   |
| No component-matching condition for obtaining five responses | No    | No    | Yes   | Yes   | Yes   | Yes   |
| No need of input inverting/matching for obtaining five filtering responses | Yes   | No    | Yes   | Yes   | Yes   | Yes   |
| Offer electronic controls                   | Yes   | Yes   | Yes   | Yes   | Yes   | Yes   |
| Obtaining results                           | Sim   | Sim   | Sim/Exp | Sim   | Sim   | Sim/Exp |

Note: DVGA = voltage differencing gain amplifier, VDCC = voltage differencing current conveyor.

From (2), five standard filtering responses can be obtained as:

- The non-inverting LP response: $V_{\text{in}1} = V_{\text{in}3} = V_{\text{in}4} = 0$ (grounded), $V_{\text{in}2} = V_{\text{out}}$.
- The non-inverting BP response: $V_{\text{in}1} = V_{\text{in}3} = V_{\text{in}4} = 0$ (grounded), $V_{\text{in}2} = V_{\text{out}}$.
- The inverting BP response: $V_{\text{in}1} = V_{\text{in}2} = V_{\text{in}4} = 0$ (grounded), $V_{\text{in}3} = V_{\text{out}}$.
- The non-inverting HP response: $V_{\text{in}1} = V_{\text{in}2} = V_{\text{in}3} = 0$ (grounded), $V_{\text{in}4} = V_{\text{out}}$.
- The non-inverting BS response: $V_{\text{in}2} = V_{\text{in}3} = 0$ (grounded), $V_{\text{in}1} = V_{\text{in}4} = V_{\text{out}}$.

Therefore, five standard filtering responses can be obtained by appropriately applying the input signals and realization to obtain these filtering functions without component-matching conditions and inverting-type input signal requirements. The output impedance of the proposed universal filter in Fig. 2 is given by $1/g_{m5}$.

The natural frequency ($\omega_o$) and quality factor (Q) of all filtering responses can be expressed by:

\[
\omega_o = \frac{g_{m1}g_{m3}g_{m2}}{C_1C_2g_{m5}} \quad (3)
\]

\[
Q = \frac{1}{g_{m4}} \sqrt{\frac{C_1g_{m1}(g_{m2}g_{m5})}{g_{m3}}} \quad (4)
\]

Letting $g_{m2} = g_{m3} = g_{m_1}$, (3) and (4) can be rewritten as:

\[
\omega_o = \frac{g_{m1}g_{m3}g_{m2}}{C_1C_2} \quad (5)
\]
\[ Q = \frac{g_m}{g_{m4}} \frac{C_1 g_{m1}}{C_1 g_{m3}} \]  

(6)

From (3) and (6), parameter \( \omega_o \) for all filtering responses can be controlled electronically through \( g_{m1} \) and \( g_{m3} \) by keeping \( g_{m2} = g_{m5} \) and \( C_1 = C_2 \), while parameter \( Q \) can be controlled electronically and independently through \( g_m \) (\( g_m = g_{m2} = g_{m5} \)) or \( g_{m4} \) by keeping \( g_{m1} = g_{m3} \) and \( g_{m2} \) = \( g_{m5} \). This keeping is used only for easy to control parameters \( \omega_o \) and \( Q \) which is not meaning of component-matching conditions.

**Figure 3:** Three-phase quadrature oscillator modified from universal filter.

The universal biquad filter in Fig. 2 has been slightly modified to work as a three-phase quadrature oscillator as shown in Fig. 3. The oscillator can be obtained by interchanging the connections between non-inverting and inverting terminals of OTA1 and between non-inverting and inverting terminals OTA4 in Fig. 2. The inputs \( V_{in1} \), \( V_{in3} \), \( V_{in4} \) are connected to ground while the input \( V_{in3} \) will connect to the output \( V_{out} \) to creating a positive feedback loop. Thus, the transfer function between \( V_{in3} \) and \( V_{out} \) of Fig. 2 can be expressed as

\[
\frac{V_{out}}{V_{in3}} = \frac{s \left( \frac{C_1 g_{m2} g_{m3}}{g_{m5}} \right)}{s^2 C_1 C_2 + s \left( \frac{g_m g_{m2} g_{m3} g_{m4}}{g_{m5}} \right) + \left( \frac{g_{m1} g_{m2} g_{m3} g_{m4}}{g_{m5}} \right)}
\]

(7)

Setting \( V_{out}/V_{in3} = 1 \), \( V_{out} \) is connected to \( V_{in3} \), characteristic equation of quadrature oscillator can be expressed by

\[
s^2 + s \left( \frac{g_{m1} g_{m3}}{C_2 g_{m5}} \right) \left( g_{m4} - g_{m2} \right) + \left( \frac{g_{m1} g_{m3} g_{m2} g_{m5}}{C_1 C_2 g_{m5}} \right) = 0
\]

(8)

The condition of oscillator (CO) and frequency of oscillation (FO) can be expressed respectively by

\[
g_{m4} = g_{m2}
\]

(9)

\[
\omega_o = \sqrt{\frac{g_{m1} g_{m3}}{C_1 C_2} g_{m5}}
\]

(10)

Letting \( g_{m2} = g_{m5} \), (10) can be simply expressed by

\[
\omega_o = \sqrt{\frac{g_{m1} g_{m3}}{C_1 C_2}}
\]

(11)

From (9) and (11), it is evident that the CO can be controlled electronically by \( g_{m1} \) and keeping \( g_{m2} = g_{m5} \) and the FO can be controlled electronically and independently by \( g_{m3} \) and/or \( g_{m2} \) and keeping \( C_1 = C_2 \). Thus, the proposed quadrature oscillator provides electronically and independently control of CO and FO.

It should be noted that the quadrature oscillator in Fig. 3 provides three output terminals \( V_{out1}, V_{out2}, \) and \( V_{out3} \). To express that three output terminals provide sinusoidal with 90° phase different, the transfer functions can be expressed by

\[
\frac{V_{out2}}{V_{out1}} = \frac{g_{m1}}{s C_1}
\]

(12)

\[
\frac{V_{out3}}{V_{out2}} = \frac{g_{m2}}{s C_2}
\]

(13)

Letting \( s = j \omega_o \), (12) and (13) can be rewritten respectively as

\[
V_{out1} = j \left( \omega_o C_1 / g_{m1} \right) V_{out2}
\]

\[
V_{out2} = j \left( \omega_o C_2 / g_{m2} \right) V_{out3}
\]

which indicates that the voltages \( V_{out1}, V_{out2}, V_{out3} \) are in the quadrature form.

The universal filter in Fig. 2 and quadrature oscillator in Fig. 3 can be blended into single topology. Fig. 4 shows the proposed programmable universal filter and quadrature oscillator. Universal filter and quadrature oscillator can be programmed by analog switches SW1 and SW2. The commercially available analog switches i.e., MAX14689, MAX4735, TMUX1136, TS3A44159, CD4016B, can be used to implement switches SW1 and SW2. Assume that analog switch MAX14689 [58] is used in Fig. 4 for selecting a universal filter or a quadrature oscillator.

The status of switch can be controlled by CB (i.e., logic “0” or “1”). Assume that the present status of SW1 and
SW as shown Fig. 4 is CB = 0 (i.e., “0” = 0V), the circuit will be worked as a quadrature oscillator by connecting \( V_{in2} \) and \( V_{in4} \) to ground. Three-phase outputs can be obtained as \( V_{out1} \), \( V_{out2} \), \( V_{out3} \). It should be noted that the operation of the circuit in this case is similar the quadrature oscillator in Fig. 3. Continually, if the status of SW1 and SW2 is CB = 1 (i.e., “1” = 5V), the circuit in Fig. 4 will be operated as a universal filter by applying the input signals to \( V_{in1} \), \( V_{in2} \), \( V_{in3} \), \( V_{in4} \) while the output signal is obtained as \( V_{out1} \). The operation of circuit in this case is similar the universal filter in Fig. 2. Therefore, the proposed circuit can be worked as universal filter and quadrature oscillator by programming technique. There is no topology that operates similar the proposed circuit available in open literature. The condition for obtaining universal filter and quadrature oscillator is concluded in Table 3.

Table 3: Using proposed programmable universal filter and quadrature oscillator

| Circuit type         | SW1 and SW2 | Input terminal          | Output node                  |
|----------------------|-------------|-------------------------|-----------------------------|
| Quadrature oscillator| CB=0        | \( V_{in2}=V_{in4}=0 \) (grounded) | \( V_{out1}, V_{out2}, V_{out3} \) |
| Universal filter     | CB=1        | \( V_{in1}, V_{in2}, V_{in3}, V_{in4} \) | \( V_{out1}=V_{out} \) |

3 Non-ideal analysis

Considering non-idealities of OTA, non-ideal transconductance gain \( g_{mn} \) is given by

\[
g_{mn}(s) = \frac{g_ml}{s + \omega_{gi}}
\]  

where \( \omega_{gi} \) and \( g_m \) denote the first-order pole frequency and the open-loop transconductance gain of OTA (\( i = 1, 2, .., n \)). In the frequency range of interest of this paper, \( g_{mn} \) can be modified as \( (15) \)

\[
g_{mn}(s) \equiv g_m (1 - \mu_s s)
\]  

where \( \mu_s = 1/\omega_{gi} \).

Consider first-order pole frequency \( \omega_{gi} \) it is a result of the parasitic input and output resistances (\( R_{in} \) and \( R_o \)) and the input and output capacitances (\( C_{in} \) and \( C_o \)) as shown in Fig. 5. The high-resistance and small-capacitance values will be resulted to high-value of \( \omega_{gi} \) and small-value of \( \mu_s \).

Using (15), denominator of transfer function of universal filter can be written as

\[
s^3C_{g_{m1}}g_{m1}(L_{m1})(1-B)+s^{3}C_{g_{m2}}C_{g_{m3}}(1-C)+sC_{g_{m2}}g_{m2}(1-D)+A
\]  

where

\[
A = g_{m1}g_{m2}g_{m2}
\]
\[ B = \frac{C_1 C_2 \mu_1 + A \mu_1 \mu_2 \mu_3}{C_1 G_{m3} G_{m4}} \]
\[ C = \frac{C_1 G_{m1} G_{m2} \mu_1 + C_1 G_{m1} G_{m2} \mu_2 - A \mu_1 \mu_2 - A \mu_1 \mu_3 - A \mu_2 \mu_3}{C仅仅是数} \]
\[ D = \frac{A \mu_1 + A \mu_2 + A \mu_3}{C_4 G_{m3} G_{m4}} \]

For the effect of OTA parasitic elements, it can be neglected by satisfying the following condition:

\[
\begin{align*}
B &\equiv \mu_3 \mu_4 \\
C &<< 1 \\
D &<< 1
\end{align*}
\]

(17)

The various passive and active sensitivities on the parameters \(\omega_0\) and \(Q\) of the universal filter can be expressed as

\[
S_{\omega_0}^{\Delta \omega_0} = S_{\omega_0}^{\Delta \omega_0} = S_{C_2}^{\Delta C_2} = S_{C_2}^{\Delta C_2} = \frac{1}{2}
\]

(18)

\[
S_{\omega_a}^{\Delta \omega_a} = S_{\omega_a}^{\Delta \omega_a} = S_{C_2}^{\Delta C_2} = S_{C_2}^{\Delta C_2} = \frac{1}{2}
\]

(19)

\[
S_{\omega_a}^{\Delta \omega_a} = -1
\]

(20)

Thus, all incremental parametric sensitivities for parameters \(\omega_0\) and \(Q\) are within 1 which has low active and passive sensitivities.

4 Simulation and experimental results

4.1 Simulation results

The proposed universal filter and quadrature oscillator has been simulated using 0.18 \(\mu\)m CMOS technology from TSMC. The CMOS OTA in Fig. 6 [59] was used and the switch was implemented using MOS transistors as shown in Fig. 7. If \(CB = \text{logic “}0\text{”}\), switch will be turned on and it will be turned-off if \(CB = \text{logic “}1\text{”}\). Fig. 8 shows analog switch that used to program universal filter and quadrature oscillator and its operation was similar Table 2. The power supply of \(\pm 1.2\) V was used. The aspect ratios of NMOS and PMOS were given respectively as \(5\mu m/1\mu m\) and \(10\mu m/1\mu m\) [59]. The logic “0” of 0 V and logic “1” of 1.2 V were given. The performances of OTA and MOS switch were summarized in Table 4.

![Figure 6: CMOS implementation for OTA [59].](image)

![Figure 7: Switch implementation: (a) symbol, (b) MOS switch, (c) CMOS inverter.](image)

![Figure 8: Analog switch.](image)

| Parameter | Value |
|-----------|-------|
| Technology | 0.18 \(\mu\)m |
| Power supply | \(\pm 1.2\) V |
| **OTA** | |
| \(g_m\) \((\text{labc}=1\text{-}50\mu\text{A})\) | 12 to 220 \(\mu\text{A}/\text{V}\) |
| Bandwidth (-3dB) \(\text{@ I}_{\text{abc}}=1\mu\text{A}\) | 20 MHz |
| \(\text{@ I}_{\text{abc}}=50\mu\text{A}\) | 300 MHz |
| Parasitic parameters \(\text{@ I}_{\text{abc}}=50\mu\text{A}\) | 38.6 MΩ/18 fF |
| Power consumption \(\text{@ I}_{\text{abc}}=50\mu\text{A}\) | 240 \(\mu\text{W}\) |
| **MOS switch** | |
| \(R_{on}\) | 320 Ω |
| \(R_{off}\) | 380 MΩ |
parameters of OTAs which deeper the notch of attenuation can be obtained when the filter was operated as lower natural frequency. Fig. 10 shows the simulated frequency responses of the gain and phase characteristics of the AP filter. It was evident from Figs. 9 and 10 that the proposed circuit provides five standard filtering responses without inverting-type input signal.

Fig. 11 shows the simulated frequency response of BP filter when the biasing currents \( I_{abc} \) were respectively adjusted for the values of 5, 10, 20 and 50 \( \mu A \). This result was confirmed that the natural frequency can be electronically controlled. Fig. 12 shows the simulated frequency response of BP filter when the biasing current \( I_{abc4} \) was respectively varied for the values of 2, 5, 20, and 50 \( \mu A \). This result was confirmed that the proposed circuit provides orthogonal and electronic controls for parameters \( \omega_0 \) and Q.

Figure 9: Simulated frequency responses of LP, HP, BP, and BS filters.

Figure 10: Simulated gain and phase responses of AP filters.
Figure 11: Simulated frequency responses of BP with different $\omega_o$.

Figure 12: Simulated frequency responses of BP with different $Q$.

Figure 13: Simulated histogram of Monte-Carlo analysis for BP filter.

The Monte Carlo analysis of the frequency response with 5% variations of the transistor threshold voltage was performed. Fig. 13 shows the results of Monte Carlo analysis using 200 runs. From the derived histogram of $f_o$, it can be expressed that the standard deviation ($\sigma$) was 1.626 kHz, the mean was 1.028 MHz and there-}

for the minimal and maximal of $f_o$ were 1.021 MHz and 1.032 MHz, respectively. This result can be used to confirm the reliability of circuit functionality in case transistor mismatch on the CMOS OTA-based filter.

The dependence of the output harmonic distortion of low-pass filter on input voltage amplitude was shown in Fig. 14. It expresses that the THD was below 1 % for the input signal of 320 mV (peak).

Second case, the circuit has been operated as a quadrature oscillator by setting $CB= "0" (0V)$. The biasing

Figure 14: Simulated THD of LP filter

Figure 15: (a) simulated of the quadrature outputs $V_{out1}$, $V_{out2}$, $V_{out3}$, (b) steady state.
current $I_{abc} (\cong 18.6 \mu A)$ was used to adjust $g_{\text{out}}$ for controlling the condition of oscillator. Fig. 15 shows the quadrature sinusoidal output waveforms of oscillator. This result shows a frequency of 0.95 MHz whereas theoretical value was 1.01 MHz. Fig. 16 shows the plot of the frequency of oscillation for varying the value of bias currents $I_{abc}$ ($I_{abc}=I_{abc}$) from 5 to 50 $\mu A$. Theoretical value was used to confirm simulation results.

Fig. 17 shows output signal levels of $V_{\text{out1}}, V_{\text{out2}}$, and $V_{\text{out3}}$ versus the frequency of oscillation. Total harmonic distortion (THD) and phase error were respectively shown in Figs. 18 and 19.

Figure 16: Simulated frequency of oscillation against biasing currents.

Figure 17: Simulated frequency of oscillation against voltage output amplitude.

4.2 Experimental results

To check the workability of proposed circuit, simulation and experiment tests have been performed simultaneously. The circuit was evaluated by SPICE simulator and experiment test using commercial OTA LM13600 [60]. The switches $SW_1$ and $SW_2$ were implemented using 4-channel analog switch CD4016B [61] and it was also available in PSPICE library. Fig. 20 shows the design of

First case, the circuit will be operated as universal filter. The transconductances $g_{m1} = g_{m2} = g_{m3} = g_{m4} = g_{m5} = 1.512 \text{ mS}$ ($g_{m} = I_{ABC}/2V_T$, $I_{ABC} = 78.02 \mu A$) were designed to obtain the filter with natural frequency of $f_o = 109.38$ kHz and quality factor of $Q = 1$. The bias current $I_{ABC}$ of 78.02 $\mu A$ can be obtained by using resistance ($R_{ABC}$) of 47 k$\Omega$. To obtain $CB = \text{logic “0”}$ and $CB = \text{logic “1”}$, the voltage was set respectively as 0 V and 5 V.

Fig. 21 shows magnitude responses of LP, HP, BP, and BS responses with natural frequency of $f_o = 109$ kHz. Fig. 22 shows magnitude and phase responses of AP filter. Fig. 23 shows magnitude responses of BP filters when the values of $g_{m}$ ($g_{m} = g_{m1} = g_{m3}$) were varied with the
values of 0.481 mS ($I_{ABC} = 24.84 \mu A, R_{ABC} = 150 \Omega$), 0.873 mS ($I_{ABC} = 45.06 \mu A, R_{ABC} = 82 \Omega$), 1.512 mS ($I_{ABC} = 151.4 \mu A, R_{ABC} = 24 \Omega$) and 5.81 mS ($I_{ABC} = 299.8 \mu A, R_{ABC} = 12 \Omega$). In Fig. 23, the natural frequency $f_o$ was varied from 38.9 kHz, 63.2 kHz, 109 kHz, 212.3 kHz and 419.7 kHz when $g_m$ was varied respectively from 0.481 mS, 0.873 mS, 1.512 mS, 2.934 mS and 5.81 mS. Fig. 24 shows magnitude responses of BP filters when the values of $g_m$ ($g_{m2} = g_{m5} = g_m$) were varied with different values of 0.873 mS, 1.512 mS, 2.934 mS, 5.81 mS, 8.45 mS ($I_{ABC} = 436.3 \mu A, R_{ABC} = 8.2 \Omega$) to express different parameter $Q$, while $g_{m4}$ was fixed as 1.512 mS.

The LP filter has been used to test the distortion of the universal filter by setting the natural frequency of 109 kHz and applying the input frequency of 1 kHz. Fig. 25 shows total harmonic distortion (THD) parameter of the LP filter when the amplitude was varied. It expresses that the amplitude of 115 mV (peak), THD was 1%.

Temperature stability of the proposed filter on parameter $\omega_o$ was simulated by varying temperature from -10º to 80º which was shown in Fig. 26. When the temperature was varied from -10 to 80 º, the corresponding $f_o$...
was changed from 120.5 kHz to 97 kHz. Temperature stability has been investigated because BJT OTA was used in this case, better temperature stability will be obtained if CMOS OTA was used.

The proposed quadrature oscillator was also evaluated by SPICE simulation and experiment test using commercial OTA LM13600. The parameter was set similar the case of universal filter. Namely, the supply voltages were $V_{DD} = -V_{SS} = 5 \text{ V}$ and the capacitances $C_1$ and $C_2$ were 2.2 nF. The measured output waveforms were taken using Tektronix MSO 4034 mixed signal oscilloscope (4-channel oscilloscope).

Fig. 27 shows measured output wave forms of $V_{out1}$, $V_{out2}$ and $V_{out3}$ when the circuit was designed as $g_{m1} = g_{m2} = g_{m3} = g_{m5} = 1.512 \text{ mS}$ ($R_{ABC} = 47 \text{ k}\Omega$) and $g_{m4}$ was varied as 1.48 mS ($R_{ABC} = 48 \text{ k}\Omega$), the circuit generates the frequency of 96.7 kHz while theoretical value was 109.38 kHz, and the amplitudes were nearly equaled. The quadrature output form in Fig. 28 was verified through the XY mode. The quadrature relationships between $V_{out1}$ and $V_{out3}$ and between $V_{out2}$ and $V_{out3}$ were shown in Fig. 28, (a) and (b), respectively.

The experimental result of the FO by changing the value of transconductances $g_m$ ($g_m = g_{m1} = g_{m3}$) was shown in Fig. 29. From this figure, when the transconductances $g_m$ was changed as 0.481 mS ($R_{ABC} = 150 \text{ k}\Omega$), 0.873 mS ($R_{ABC} = 82 \text{ k}\Omega$), 1.512 mS ($R_{ABC} = 47 \text{ k}\Omega$), 2.934 mS ($R_{ABC} = 24 \text{ k}\Omega$), 5.81 mS ($R_{ABC} = 12 \text{ k}\Omega$), 8.45 mS ($R_{ABC} = 8.2 \text{ k}\Omega$), the FO was changed respectively as 32.7 kHz, 58.5 kHz, 96.7 kHz, 200 kHz, 395 kHz, and 580 kHz. The theoretical value has been used to compare the experimental result.

The plot for amplitude versus FO was shown in Fig. 30. Compared with Fig. 17, it should be noted that when $g_m$ ($g_m = g_{m1} = g_{m3}$) was varied far from 1.512 mS, the amplitude of $V_{out1}$ and $V_{out3}$ will increase while the amplitude of $V_{out2}$ will decrease when the FO was increased. If the constant amplitude of output signals was required, it can be obtained using the amplitude-automatic gain control (AGC) circuit [57]. The THD of output signals $V_{out1}$, $V_{out2}$ and $V_{out3}$ was plotted and shown in Fig. 31. It should be noted that large amplitude of output signal will be suffered from high THD. Fig. 32 shows the phase error that outputs between $V_{out1}$ and $V_{out2}$, between $V_{out2}$ and $V_{out3}$ deviated from 90° phase different.
output universal filter that can be realized LP, BP, HP, BS, and AP voltage responses by applying the input terminals appropriately at high input impedance. The natural frequency and the quality factor can be controlled electronically and independently by adjusting the bias currents of OTAs. Neither component-matching con-

5 Conclusions

In this paper, a new programmable voltage-mode universal filter and quadrature oscillator using five single output OTAs and two grounded capacitors is presented. The circuit uses analog switch to program either a universal filter or a quadrature oscillator. When the circuit performs function as filter, it is a four-input single-
ditions nor inverting-type input signals is required for obtaining five standard filtering functions. When the circuit works as quadrature oscillator, it is a three-phase quadrature oscillator that the condition and frequency of oscillation of oscillator can be independently and electronically controlled. The proposed structure is realized based on single output OTAs which is easily implemented in both as commercially available ICs as OTAs and CMOS as IC forms. The functionality of the proposed circuit is confirmed by SPICE simulation and experiment test.

6 Acknowledgments

This work was supported by King Mongkut's Institute of Technology Ladkrabang under grant KREF026201.

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