Original scientific paper

https://doi.org/10.33180/InfMIDEM2021.403

Informacije MIDEM
Journal of Microelectronics,
Electronic Components and Materials
Vol. 51, No. 4(2021), 225 – 241

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

Boonying Knobnob[1], *Usa Torteanchai*[2], *Montree Kumngern*[3]

[1]*Faculty of Engineering, Rajamangala University of Technology Thanyaburi, Pathum Thani, Thailand*
[2]*Aeronautical Engineering Division, Civil Aviation Training Center, Bangkok, Thailand*
[3]*Department of Telecommunications Engineering, School of Engineering, King Mongkut's Institute of Technology Ladkrabang, Bangkok, Thailand*

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 oscilator z uporabo enojnih izhodnih operacijskih transkonduktančnih ojačevalnikov

Izvleček: Članek predstavlja nov programirljiv univerzalni filter in kvadraturni oscilator, ki temelji na enojnih izhodnih operacijskih transkonduktančnih ojačevalnikih (OTA). Predlagani univerzalni filter in kvadraturni oscilator je mogoče s programiranjem analognih stikal združiti v enotno topologijo. Ko vezje deluje kot univerzalni filter, lahko izvede nizkoprepustne, visokoprepustne, pasovne, zaporne in vseprepustne filtre z ortogonalnim in elektronskim upravljanjem lastne frekvence in faktorja kakovosti. Če vezje deluje kot kvadraturni oscilator, 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 OTA, ki jih je mogoče enostavno izvesti tako v obliki komercialno dostopnih integriranih vezij (IC) kot OTA kot komplementarnih kovinsko oksidnih polprevodniških (CMOS) OTA 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 oscilator; operacijski transkonduktančni ojačevalnik; analogna obdelava signalov; napetostno vezje

---

** Corresponding Author's e-mail: montree.ku@kmitl.com*

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

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 paralled using discrete component ICs, the number of devices utilized will equal the number of required outputs, incresing 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. Futhermore, 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

$$I_o = g_m\left(V_{in+} - V_{in-}\right) \tag{1}$$

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-CCCII	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 ω_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 ω_o and Q of filter	Yes	No	Yes	Yes	Yes	Yes
No component-matching condition for obtaining five responses	No	No	Yes	No	No	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.

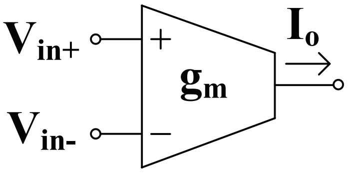


Figure 1: Electrical symbol of OTA.

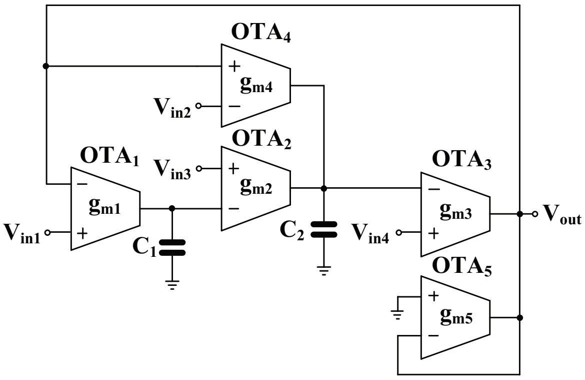


Figure 2: Universal biquad filter using single output OTAs.

Fig. 2 shows the voltage-mode universal biquad filter with four-input single-output using single output OTAs. This work is continuously developed next from previous work in [14]. The input signals V_{in1}, V_{in2}, V_{in3} and V_{in4} of filter are supplied to high impedance terminals of OTAs (infinite for ideal case), thus it requires no buffer circuits because the loading effect is vanished.

If V_{in1}, V_{in2}, V_{in3} and V_{in4} are input signal voltages, the output voltage of the proposed filter can be expressed by

$$V_{out}=\frac{s^2C_1C_2\left(\frac{g_{m3}}{g_{m5}}\right)V_{in4}-s\left(\frac{C_1g_{m2}g_{m3}}{g_{m5}}\right)V_{in3}+s\left(\frac{C_1g_{m3}g_{m4}}{g_{m5}}\right)V_{in2}+\left(\frac{g_{m1}g_{m2}g_{m3}}{g_{m5}}\right)V_{in1}}{s^2C_1C_2+s\left(\frac{C_1g_{m3}g_{m4}}{g_{m5}}\right)+\left(\frac{g_{m1}g_{m2}g_{m3}}{g_{m5}}\right)} \quad (2)$$

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

The non-inverting LP response: $V_{in2}=V_{in3}=V_{in4}=0$ (grounded), $V_{in1}=V_{in}$.

The non-inverting BP response: $V_{in1}=V_{in3}=V_{in4}=0$ (grounded), $V_{in2}=V_{in}$.

The inverting BP response: $V_{in1}=V_{in2}=V_{in4}=0$ (grounded), $V_{in3}=V_{in}$.

The non-inverting HP response: $V_{in1}=V_{in2}=V_{in3}=0$ (grounded), $V_{in4}=V_{in}$.

The non-inverting BS response: $V_{in2}=V_{in3}=0$ (grounded), $V_{in1}=V_{in4}=V_{in}$.

The non-inverting AP response: $V_{in2}=0$ (grounded), $V_{in1}=V_{in3}=V_{in4}=V_{in}$.

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 (ω_o) and quality factor (Q) of all filtering responses can be expressed by

$$\omega_o=\sqrt{\frac{g_{m1}g_{m3}}{C_1C_2}\cdot\frac{g_{m2}}{g_{m5}}} \quad (3)$$

$$Q=\frac{1}{g_{m4}}\sqrt{\frac{C_2g_{m1}}{C_1g_{m3}}\left(g_{m2}g_{m5}\right)} \quad (4)$$

Letting $g_{m2} = g_{m5} = g_m$, (3) and (4) can be rewritten as

$$\omega_o=\sqrt{\frac{g_{m1}g_{m3}}{C_1C_2}} \quad (5)$$

$$Q = \frac{g_m}{g_{m4}}\sqrt{\frac{C_2 g_{m1}}{C_1 g_{m3}}} \tag{6}$$

From (3) and (6), parameter ω_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 $C_1 = C_2$. This keeping is used only for easy to control parameters ω_o and Q which is not meaning of component-matching conditions.

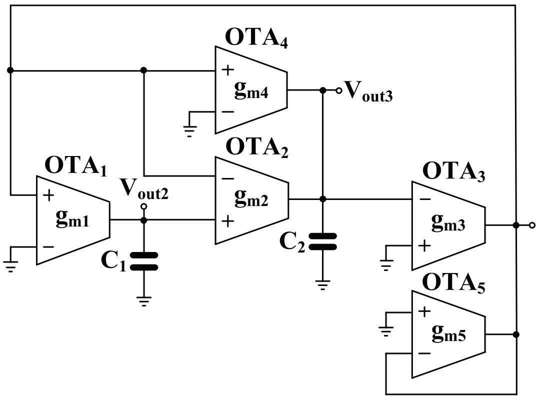


Figure 3: Three-phase quadrature oscillator modified from universal filter.

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 OTA_1 and between non-inverting and inverting terminals OTA_2 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_{out} and V_{in3} of Fig. 2 in case work as oscillator can be expressed as

$$\frac{V_{out}}{V_{in3}} = \frac{s\left(\frac{C_1 g_{m2} g_{m3}}{g_{m5}}\right)}{s^2 C_1 C_2 + s\left(\frac{C_1 g_{m3} g_{m4}}{g_{m5}}\right) + \left(\frac{g_{m1} g_{m2} g_{m3}}{g_{m5}}\right)} \tag{7}$$

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

$$s^2 + s\frac{g_{m3}}{C_2 g_{m5}}\left(g_{m4} - g_{m2}\right) + \left(\frac{g_{m1} g_{m3}}{C_1 C_2} . \frac{g_{m2}}{g_{m5}}\right) = 0 \tag{8}$$

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

$$g_{m4} = g_{m2} \tag{9}$$

$$\omega_o = \sqrt{\frac{g_{m1} g_{m3}}{C_1 C_2} . \frac{g_{m2}}{g_{m5}}} \tag{10}$$

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

$$\omega_o = \sqrt{\frac{g_{m1} g_{m3}}{C_1 C_2}} \tag{11}$$

From (9) and (11), it is evident that the CO can be controlled electronically by g_{m4} and keeping $g_{m2} = g_{m5}$ and the FO can be controlled electronically and independently by g_{m1} and/or g_{m3} 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

$$\frac{V_{out2}}{V_{out1}} = \frac{g_{m1}}{sC_1} \tag{12}$$

$$\frac{V_{out3}}{V_{out2}} = \frac{g_{m2}}{sC_2} \tag{13}$$

Letting $s = j\omega_o$, (12) and (13) can be rewritten respectively as $V_{out1} = j\left(\omega_o C_1 / g_{m1}\right) V_{out2}$ and $V_{out2} = j\left(\omega_o C_2 / g_{m2}\right) V_{out3}$ 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 SW_1 and SW_2. The commercially available analog switches i.e., MAX14689, MAX4735, TMUX1136, TS3A44159, CD4016B, can be used to implement switches SW_1 and SW_2. 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 SW_1 and

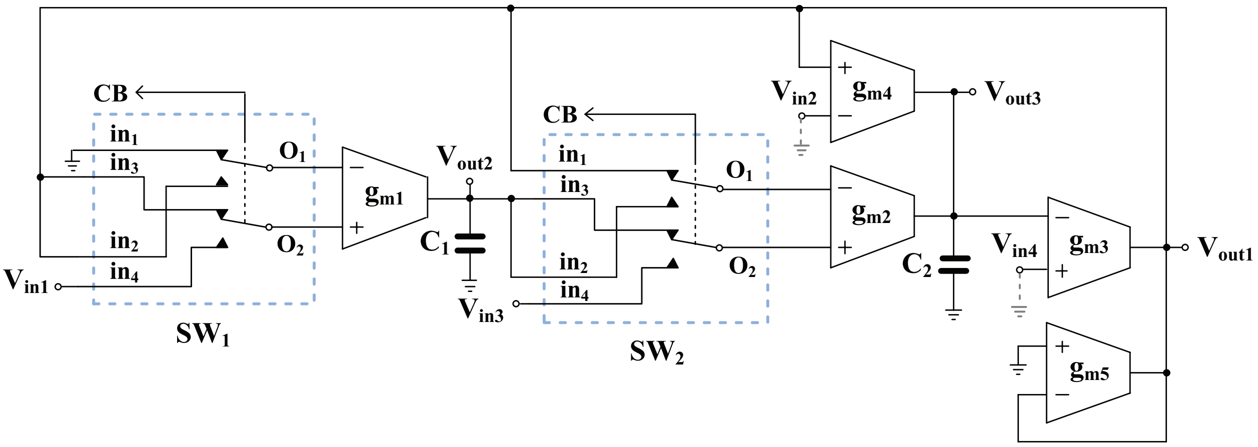


Figure 4: Proposed programmable filter and quadrature oscillator.

SW_2 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 SW_1 and SW_2 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} and 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	SW_1 and SW_2	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_{mni} is given by

$$g_{mni}(s) = \frac{g_{mi}\omega_{gi}}{s + \omega_{gi}} \tag{14}$$

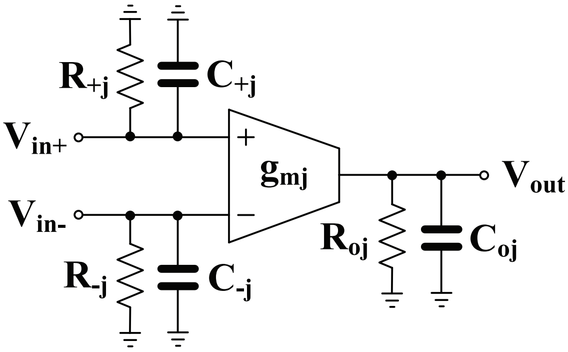


Figure 5: Modeling the non-idealities in the OTA [16].

where ω_{gi} and g_{mi} denote the first-order pole frequency and the open-loop transconductance gain of OTA_i (i = 1, 2, .., n). In the frequency range of interest of this paper, g_{mni} can be modified as [17]

$$g_{mni}(s) \cong g_{mi}(1 - \mu_i s) \tag{15}$$

where $\mu_i = 1/\omega_{gi}$.

Consider first-order pole frequency ω_{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 ω_{gi} and small-value of μ_i.

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

$$s^3 C_1 g_{m3} g_{m4}(\mu_3\mu_4 - B) + s^2 C_1 C_2 (1 - C) + s C_1 g_{m3} g_{m4} (1 - D) + A \tag{16}$$

Were

$$A = g_{m1} g_{m2} g_{m3}$$

$$B = \frac{C_1 C_2 \mu_5 + A\mu_1\mu_2\mu_3}{C_1 g_{m3} g_{m4}}$$

$$C = \frac{C_1 g_{m3} g_{m4}\mu_3 + C_1 g_{m3} g_{m4}\mu_4 - A\mu_1\mu_2 - A\mu_1\mu_3 - A\mu_2\mu_3}{C_1 C_2}$$

$$D = \frac{A\mu_1 + A\mu_2 + A\mu_3}{C_1 g_{m3} g_{m4}}$$

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

$$\left.\begin{array}{l} B \cong \mu_3\mu_4 \\ C << 1 \\ D << 1 \end{array}\right\} \qquad (17)$$

The various passive and active sensitivities on the parameters ω_o and Q of the universal filter can be expressed as

$$S^{\omega_o}_{g_{m1}} = S^{\omega_o}_{g_{m2}} = S^{\omega_o}_{g_{m3}} = -S^{\omega_o}_{g_{m5}} = -S^{\omega_o}_{C_1} = -S^{\omega_o}_{C_2} = \frac{1}{2} \qquad (18)$$

$$S^{Q}_{g_{m1}} = S^{Q}_{g_{m2}} = S^{Q}_{g_{m5}} = S^{Q}_{C_2} = -S^{Q}_{g_{m3}} = -S^{Q}_{C_1} = \frac{1}{2} \qquad (19)$$

$$S^{Q}_{g_{m4}} = \text{-}1 \qquad (20)$$

Thus, all incremental parametric sensitivities for parameters ω_o 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 µm 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 = logic "0", switch will be turned on and it will be turned-off if CB = logic "1". 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 ±1.2 V was used. The aspect ratios of NMOS and PMOS were given respectively as 5µm/1µm and 10µm/1µm [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.

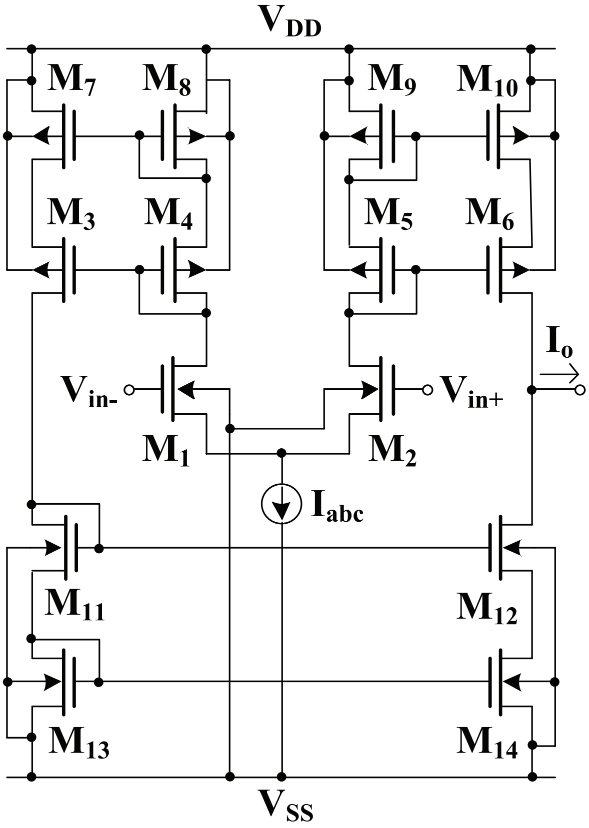
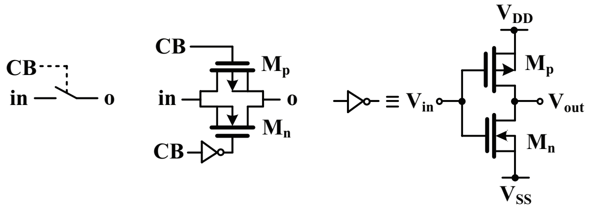


Figure 6: CMOS implementation for OTA [59].

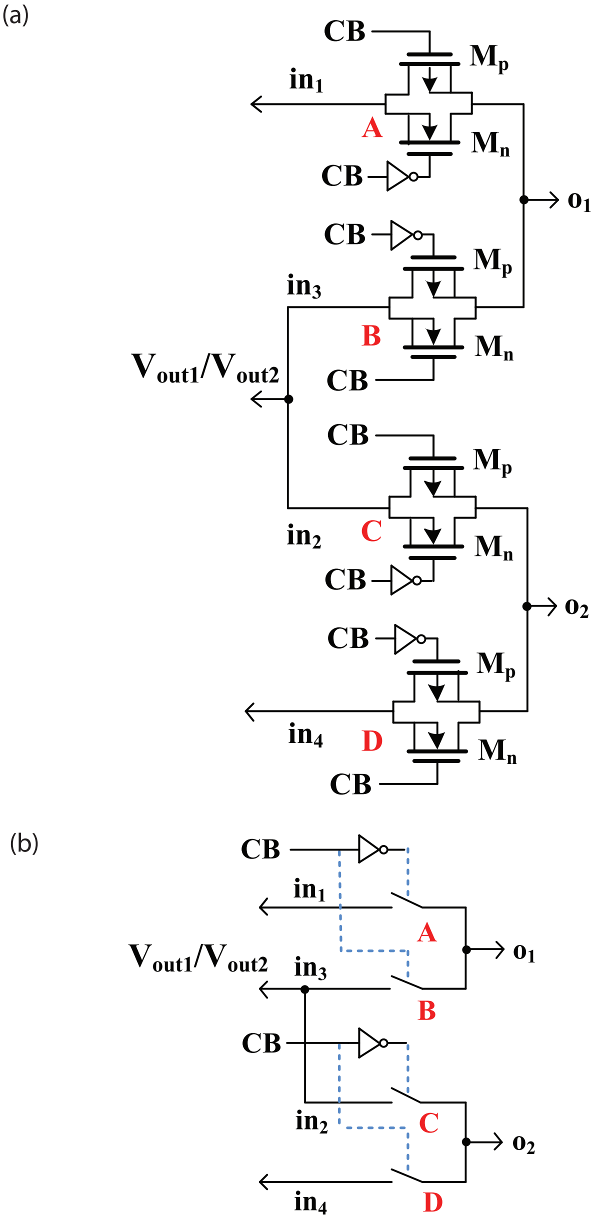


(a) (b) (c)

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

Table 4: Simulated specifications of CMOS OTA and MOS switch.

Parameter	Value
Technology	0.18 µm
Power supply	±1.2 V
OTA	
g_m (I_{abc}=1-50µA)	12 to 220 µA/V
Bandwidth (-3dB) @ I_{abc}=1 µA @ I_{abc}=50 µA	23 MHz 300 MHz
Parasitic parameters @ I_{abc}=50 µA R_o//C_o	38.6 MΩ//18 fF
Power consumption @ I_{abc}=50 µA	240 µW
MOS switch	
R_{on}	320 Ω
R_{off}	380 MΩ



Logic CB	SW A	SW B	SW C	SW D
0	NO	OFF	ON	OFF
1	OFF	ON	OFF	ON

Figure 8: Analog switch implementation: (a) circuit, (b) symbol.

First case, the circuit has been operated as a universal filter by setting CB= “1” (1.2V). The capacitors $C_1 = C_2 = 22$ pF and the bias currents $I_{abc1}=I_{abc2}=I_{abc3}=I_{abc4}=I_{abc5}=20\mu A$ ($g_m=139.86\mu S$) were designed. This setting has been designed to obtain the LP, BP, HP, BS, and AP filter responses with $f_o \cong 1$ MHz and Q=1.

Fig. 9 shows the simulated frequency responses of the LP, HP, BP, and BS filters of the proposed filter. At natural frequency, the notch depth of attenuation in case of BS filter was about -25 dB which should be less than -30 dB for an acceptable level. It causes from the parasitic 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} ($I_{abc}=I_{abc1}=I_{abc3}$) were respectively adjusted for the values of 5, 10, 20 and 50 μA. 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 μA. This result was confirmed that the proposed circuit provides orthogonal and electronic controls for parameters ω_o and Q.

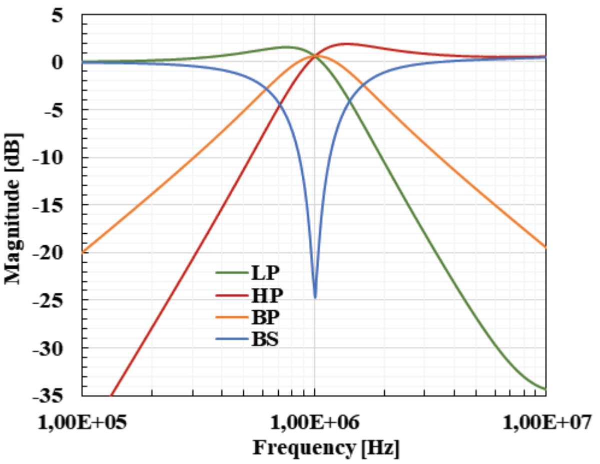


Figure 9: Simulated frequency responses of LP, HP, BP, and BS filters.

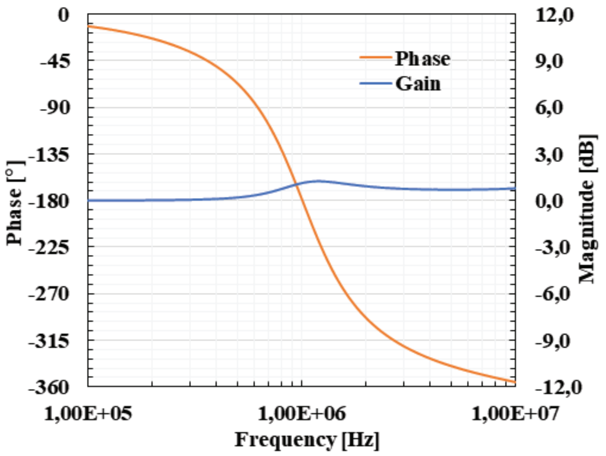


Figure 10: Simulated gain and phase responses of AP filters.

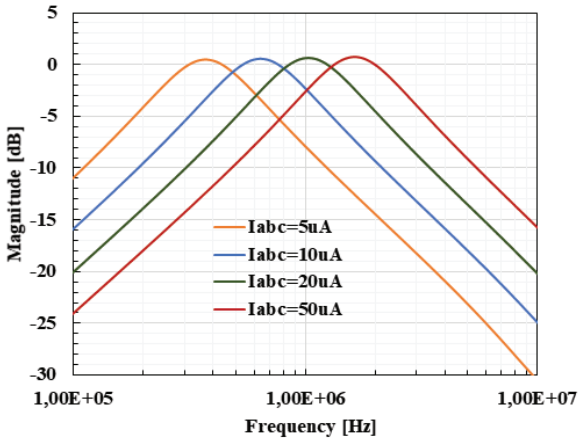


Figure 11: Simulated frequency responses of BP with different ω_o.

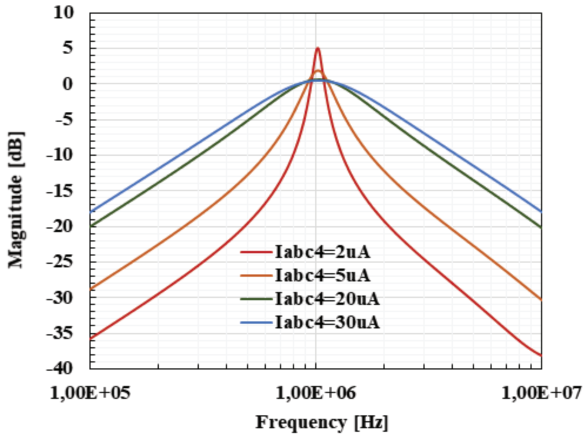


Figure 12: Simulated frequency responses of BP with different Q.

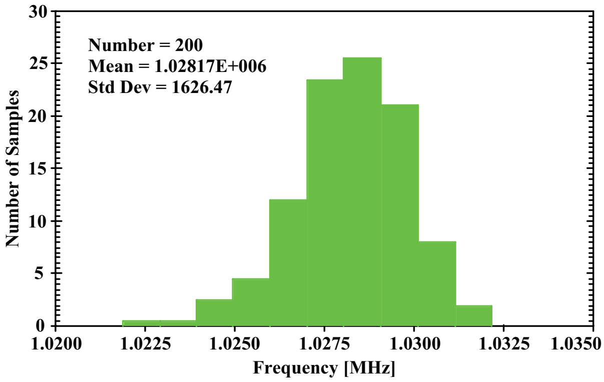


Figure 13: Simulated histogram of Monte-Carlo analysis for BP filter.

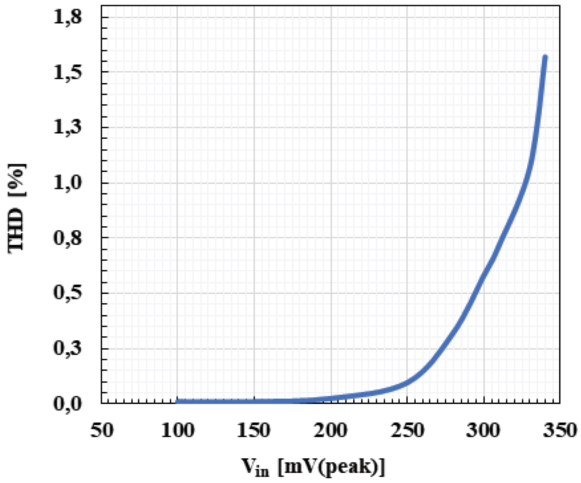


Figure 14: Simulated THD of LP filter

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 (σ) was 1.626 kHz, the mean was 1.028 MHz and therefore 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

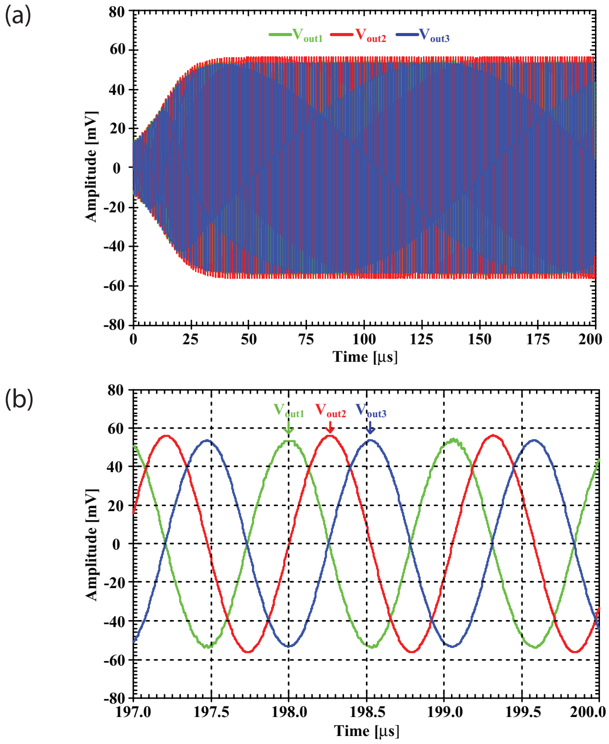


Figure 15: (a) simulated of the quadrature outputs V_{out1}, V_{out2}, V_{out3}, (b) steady state.

current I_{abc4} (≅18.6μA) was used to adjust g_{m4} 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} ($I_{abc}=I_{abc1}=I_{abc3}$) from 5 to 50μA. Theoretical value was used to confirm simulation results.

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

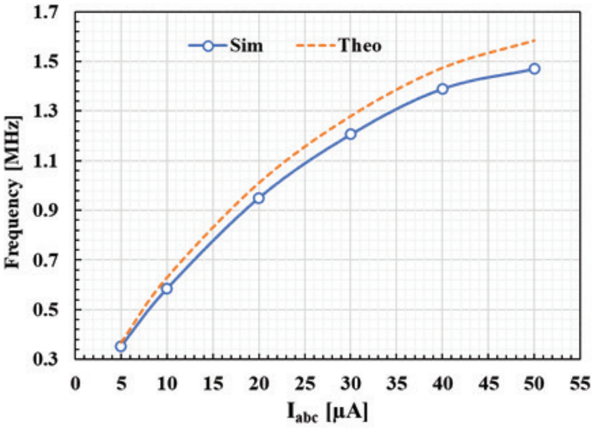


Figure 16: Simulated frequency of oscillation against biasing currents.

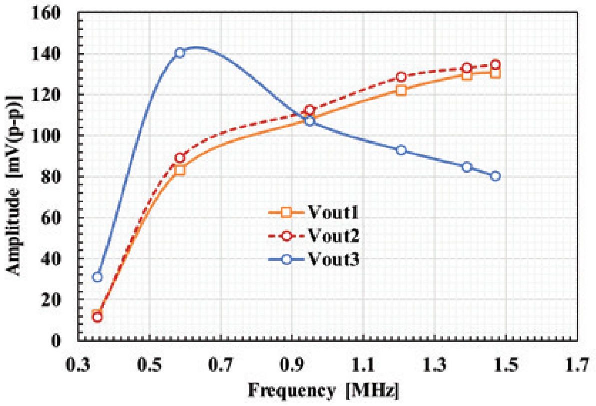


Figure 17: Simulated frequency of oscillation against voltage output amplitude.

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 SW_1 and SW_2 using 4-channel analog switch CD4016B that can be used in Fig. 4, namely CB = logic "0" for quadrature oscillator and CB = logic "1" for universal filter. The convention inverter 74LS04 have been used. The supply voltages were selected as $V_{DD} = -V_{SS} = 5$ V and capacitances C_1 and C_2 were given as 2.2 nF. The sinusoidal input signal and the measured output waveforms were taken using Agilent Technologies DSO-X 2002A oscilloscope.

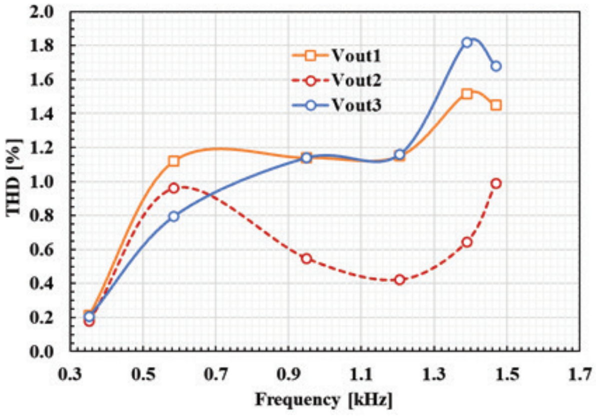


Figure 18: Simulated THD as a function of frequency of oscillation.

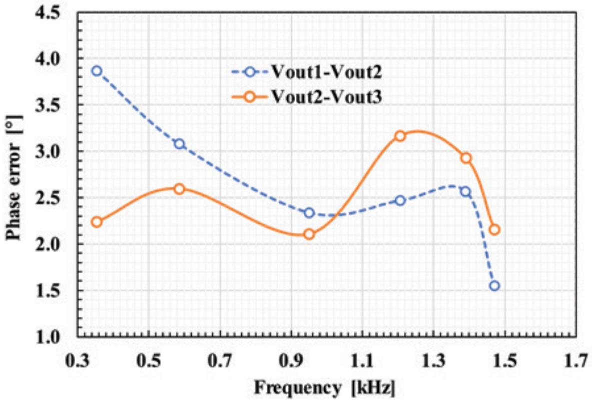
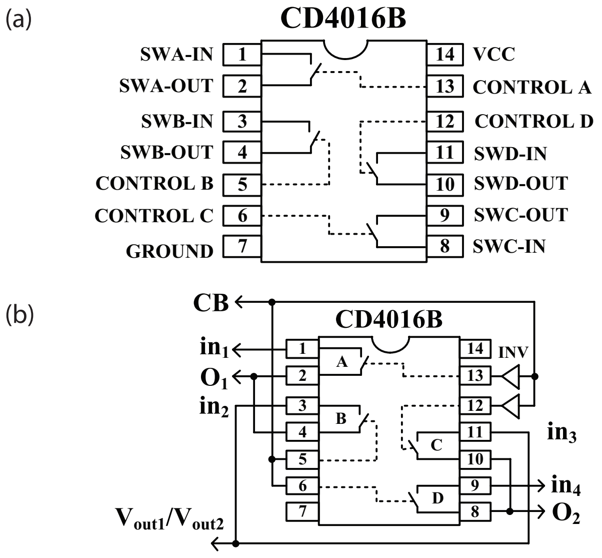


Figure 19: Simulated phase error as a function of frequency of oscillation.

First case, the circuit will be operated as universal filter. The transconductances $g_{m1} = g_{m2} = g_{m3} = g_{m4} = g_{m5} =$ 1.512 mS ($g_m = I_{ABC}/2V_T$, I_{ABC} = 78.02 μA) 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 μA can be obtained by using resistance (R_{ABC}) of 47 kΩ. To obtain CB = logic "0" and CB = 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



Logic CB	SW A	SW B	SW C	SW D
0	NO	OFF	ON	OFF
1	OFF	ON	OFF	ON

Figure 20: 4-channel analog switch CD4016B: (a) CD4016B pinout, (b) Implementation for SW_1 and SW_2.

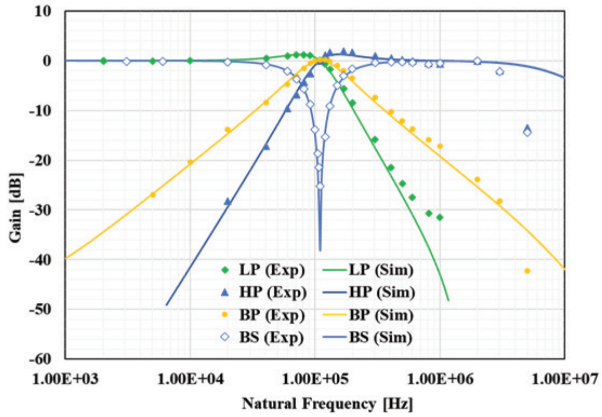


Figure 21: Magnitude responses of LP, BP, HP, and BS filter.

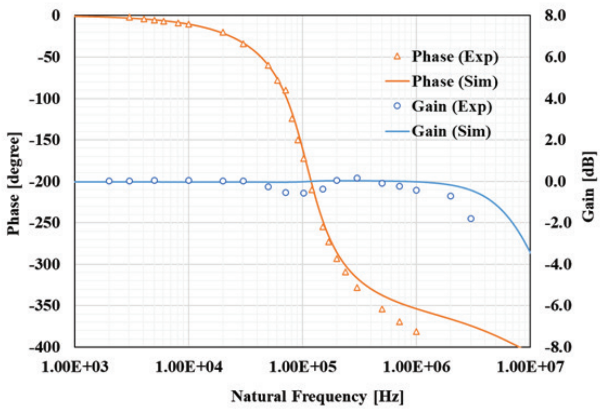


Figure 22: Magnitude and phase responses of AP filter.

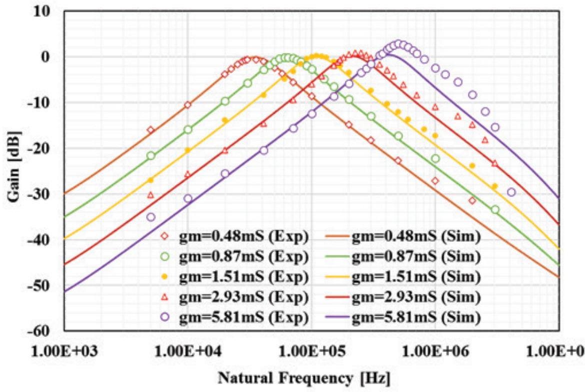


Figure 23: Magnitude responses of BP filter with different parameter ω_o.

values of 0.481 mS (I_{ABC} = 24.84 µA, R_{ABC}=150 kΩ), 0.873 mS (I_{ABC} = 45.06 µA, R_{ABC}=82 kΩ), 1.512 mS, 2.934 mS (I_{ABC} = 151.4 µA, R_{ABC}=24 kΩ) and 5.81 mS (I_{ABC} = 299.8 µA, R_{ABC} = 12 kΩ). 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 µA, R_{ABC} = 8.2 kΩ) 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 %.

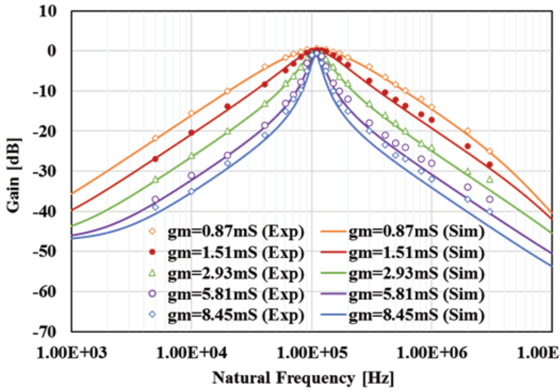


Figure 24: Magnitude responses of BP filter with different parameter Q.

Temperature stability of the proposed filter on parameter ω_o was simulated by varying temperature from -10° to 80° which was shown in Fig. 26. When the temperature was varied from -10 to 80 °, the corresponding f_o

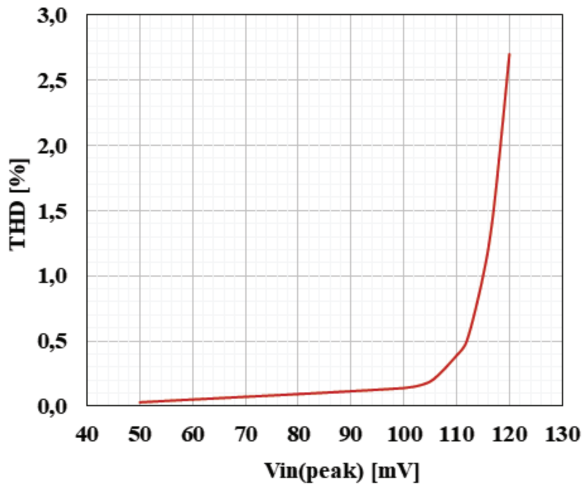


Figure 25: THD variations of the LP filter versus amplitudes of the input voltage at 1 kHz.

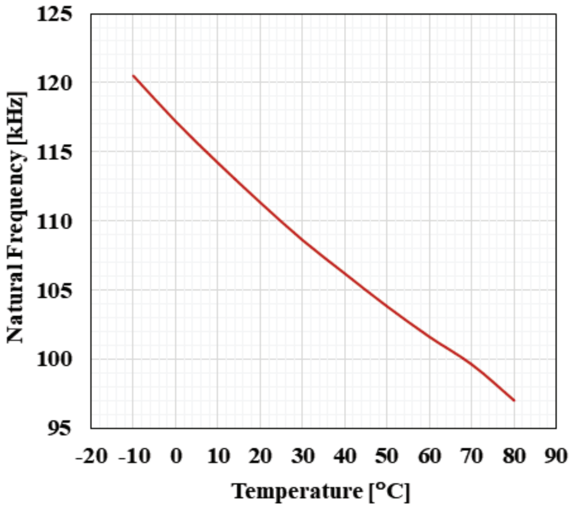


Figure 26: Natural frequency variations of the BP filter versus temperatures.

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 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 mS (R_{ABC} = 47 kΩ) and g_{m4} ≅ 1.48 mS (I_{ABC} = 76.4 µA: R_{ABC} = 48 kΩ) was used for controlling the CO. 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_{out2} 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 kΩ), 0.873 mS (R_{ABC}=82 kΩ), 1.512 mS (R_{ABC}=47 kΩ), 2.934 mS (R_{ABC}=24 kΩ), 5.81 mS (R_{ABC} = 12 kΩ), 8.45 mS (R_{ABC} = 8.2 kΩ), 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.

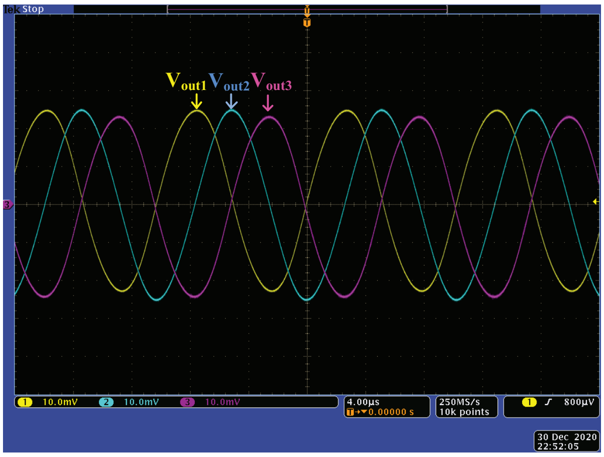


Figure 27: The experimental of quadrature outputs V_{out1}, V_{out2}, V_{out3}.

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 (lower and higher from 1.512 mS), the amplitude of V_{out1}, V_{out2} and V_{out3} will be changed. The amplitudes of V_{out1} and V_{out2} will increase while the amplitude of V_{out3} 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.

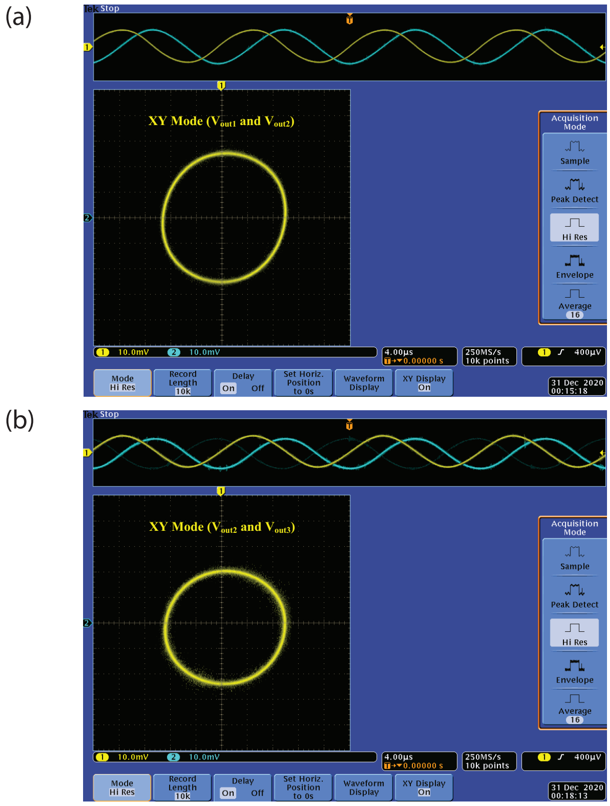


Figure 28: Lissajous pattern: (a) V_{out1} and V_{out2} outputs, (b) V_{out2} and V_{out3} outputs.

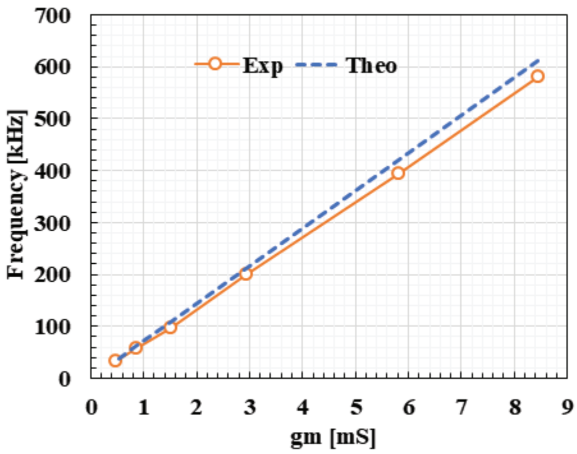


Figure 29: The frequency of oscillation against transconductances g_m.

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-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-

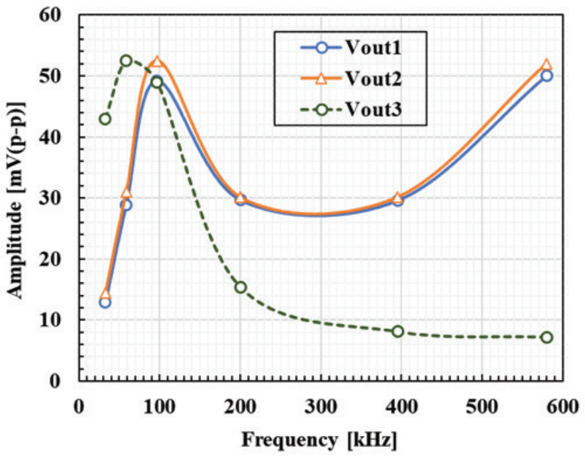


Figure 30: Output amplitude against the frequency of oscillation.

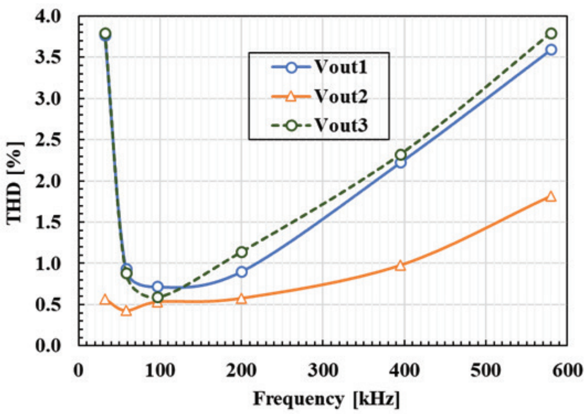


Figure 31: THD as a function of frequency of oscillation.

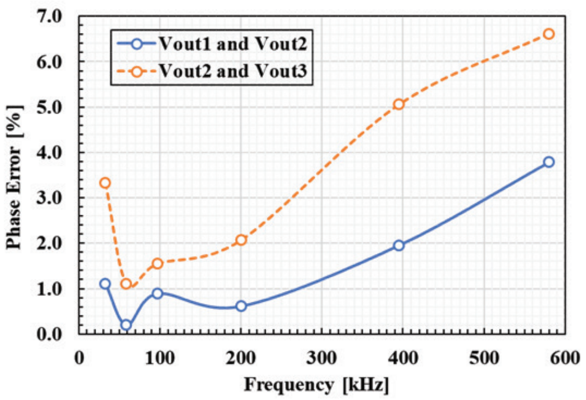


Figure 32: Phase error as a function of the frequency of oscillation.

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.

7 References

1. R. L. Geiger, E. Sanchez-Sinencio, "Active filter design using operational transconductance amplifiers: a tutorial," IEEE Circuits and Devices Magazine, vol. 1, pp. 20-32, 1985. https://doi.org/10.1109/MCD.1985.6311946
2. E. Sanchez-Sinencio, J. Ramirez-Angulo, B. Linares-Barranco, A. Rodriguez-Vazquez, "Operational transconductance amplifier-based nonlinear function syntheses," IEEE Journal of Solid-State Circuits, vol. 24, pp. 1579-1586, 1989. https://doi.org/10.1109/4.44993
3. C. K. Alexander, M. N. O. Sadiku, Fundamentals of Electric Circuits, New York, McGraw-Hill, 2004. ISBN 978-0-07-338057-5
4. R. Schaumann, M. S. Ghausi, K. R. Laker, Design of Analog Filter: Passive, Active RC, and Switched Capacitor, New Jersey, Prentice Hall, 1990. ISBN-10 0132002884
5. A. Ranjan, S. Perumalla, R. Kumar, V. John, S. Yumnam, "Second order universal filter using four-terminal floating nullor (FTFN)," Journal of Circuits, Systems and Computers, vol. 28, 1950091, 2019. https://doi.org/10.1142/S0218126619500919
6. W. Jaikla, F. Khateb, M. Kumngern, T. Kulej, R. K. Ranjan, P. Suwanjan, "0.5 V fully differential universal filter based on multiple input OTAs," IEEE Access, vol. 8, pp. 187832-187839, 2020. https://doi.org/10.1109/ACCESS.2020.3030239
7. D. Singh, S. K. Paul, "Realization of current mode universal shadow filter," AEU-International Journal of Electronics and Communications, vol. 117, 153088, 2020. https://doi.org/10.1016/j.aeue.2020.153088
8. H. Alpaslan, E. Yuce, "DVCC+ based multifunction and universal filters with the high input impedance features," Analog Integrated Circuits and Signal Processing, vol. 103, pp. 325–335, 2020. https://doi.org/10.1007/s10470-020-01643-8
9. M. T. Abuelma'atti, A. Bentrcia, "A novel mixed-mode OTA-C universal filter," International Journal of Electronics, vol. 92, pp. 375-383, 2005. https://doi.org/10.1080/08827510412331295009
10. M. Kumngern, P. Suwanjan, K. Dejhan, "Electronically tunable voltage-mode universal filter with single-input five-output using simple OTAs," International Journal of Electronics, vol. 100, pp. 1118-1133, 2013. https://doi.org/10.1080/00207217.2012.743070
11. H.-P. Chen, Y.-Z. Liao, W.-T. Lee, "Tunable mixed-mode OTA-C universal filter," Analog Integrated Circuits and Signal Processing, vol. 58, pp. 135-141, 2009. https://doi.org/10.1007/s10470-008-9228-z
12. C.-N. Lee, "Multiple-mode OTA-C universal biquad filter," Circuits, Systems, and Signal Processing, vol. 29, pp. 263-274, 2010. https://doi.org/10.1007/s00034-009-9145-0
13. M. Kumngern, B. Knobnob, K. Dejhan, "Electronically tunable high-input impedance voltage-mode universal biquadratic filter based on simple CMOS OTAs," International Journal of Electronics and Communications, vol. 64, pp. 934-939, 2010. https://doi.org/10.1016/j.aeue.2009.07.015
14. M. Kumngern, "Electronically tunable capacitor-grounded voltage-mode universal filter with three-input one-output using single-ended OTAs," in Proceedings of 2012 IEEE Symposium on Industrial Electronics & Applications (ISIEA), Indonesia, 2012, pp. 104-107. https://doi.org/10.1109/ISIEA.2012.6496608
15. N. Wattikornsirikul, M. Kumngern, "Three-input one-output voltage-mode universal filter using simple OTAs," in Proceedings of 2014 12th International Conference on ICT and Knowledge Engineering (ICT and Knowledge Engineering), Thailand, 2014, pp. 28-31. https://doi.org/10.1109/ICTKE.2014.7001530
16. C. Psychalinos, C. Kasimis, F. Khateb, "Multiple-input single-output universal biquad filter using single output operational transconductance amplifiers," International Journal of Electronics and Communications, vol. 93, pp. 360–367, 2018. https://doi.org/10.1016/j.aeue.2018.06.037
17. M. Kumngern, P. Suksaibul, F. Khateb, "Four-input one-output voltage-mode universal filter using simple OTAs," Journal of Circuits, Systems, and Computers, vol. 28, pp. 1950078 (20 pages) 2019. https://doi.org/10.1142/S0218126619500786

18. S.-F. Wang, H.-Pin Chen, Y. Ku, C.-M. Yang, "A voltage-mode universal filter using five single-ended OTAs with two grounded capacitors and a quadrature oscillator using the voltage-mode universal filter," Optik-International Journal for Light and Electron Optics, vol. 192, 162950, 2019.
https://doi.org/10.1016/j.ijleo.2019.162950
19. M. Parvizi, "Design of a new low power MISO multi-mode universal biquad OTA-C filter," International Journal of Electronics, vol. 106, pp. 440-454, 2019.
https://doi.org/10.1080/00207217.2018.1540064
20. D. R. Bhaskar, A. Raj, P. Kumar, "Mixed-mode universal biquad filter using OTAs," Journal of Circuits, Systems, and Computers, vol. 29, 2050162 (22 pages), 2020.
https://doi.org/10.1142/S0218126620501625
21. A. Raj, D. R. Bhaskar, P. Kumar, "Multiple-input single-output universal biquad filter using single output OTAs," 2018 2nd IEEE International Conference on Power Electronics, Intelligent Control and Energy Systems (ICPEICES), Delhi, India, 22-24 October 2018, pp. 1237-1240.
https://doi.org/10.1109/ICPEICES.2018.8897308
22. A. Raj, P. Kumar, D. R. Bhaskar, "Multiple-input single-output universal biquad filters using reduced number of OTAs," 2019 International Symposium on Advanced Electrical and Communication Technologies (ISAECT), Rome, Italy, 27-29 November 2019, pp. 1-4.
https://doi.org/10.1109/ISAECT47714.2019.9069693.
23. T. Tsukutani, M. Higashimura, N. Takahashi, Y. Sumi, Y. Fukai, "Versatile voltage-mode active-only biquad with lossless and lossy integrator loop," International Journal of Electronics, vol. 88, pp. 1093-1101, 2001,
https://doi.org/10.1080/00207210110071279
24. T. Tsukutani, Y. Sumi, Y. Kinucasa, M. Higashimura, Y. Fukai, "Versatile active-only biquad circuits with loss-less and lossy integrator," International Journal of Electronics, vol. 91, pp. 525-536, 2004,
https://doi.org/10.1080/00207210412331299851
25. S.-F. Wang, H.-P. Chen, Y. Ku, C.-M. Yang, "Independently tunable voltage-mode OTA-C biquadratic filter with five inputs and three outputs and its fully-uncoupled quadrature sinusoidal oscillator application," AEU-International Journal of Electronics and Communications, vol. 110, 152822, 2019,
https://doi.org/10.1016/j.aeue.2019.152822
26. S.-F. Wang, H.-P. Chen, Y. Ku, Y.-C. Lin, "Versatile tunable voltage-mode biquadratic filter and its application in quadrature oscillator," Sensors, vol. 19, 2349, 2019,
https://doi.org/10.3390/s19102349
27. S.-F. Wang, H.-P. Chen, Y.-T. Ku, C.-M. Yang, "A voltage-mode universal filter using five single-ended OTAs with two grounded capacitors and a quadrature oscillator using the voltage-mode universal filter," Optik-International Journal for Light and Electron Optics, vol. 192, 162950, 2019.
https://doi.org/10.1016/j.ijleo.2019.162950
28. S.-F. Wang, H.-P. Chen, Y. Ku, C.-L. Lee, "Versatile voltage-mode biquadratic filter and quadrature oscillator using four OTAs and two grounded capacitors," Electronics, vol. 9, 1493, 2020.
https://doi.org/10.3390/electronics9091493
29. S. Haykin, M. Moher, An introduction to analog and digital communications, John Wiley & Sons, New York, 2007. ISBN: 978-0-470-46087-0
30. W. Jaikla, S. Adhan, P. Suwanjan, M. Kumngern, "Current/voltage-controlled quadrature sinusoidal oscillators for phase sensitive detection using commercially available IC," Sensors, vol. 20, 1319, 2020.
https://doi.org/10.3390/s20051319
31. R. Sotner, J. Jerabek, L. Langhammer, J. Polak, N. Herencsar, R. Prokop, J. Petrzela, W. Jaikla, "Comparison of two solutions of quadrature oscillators with linear control of frequency of oscillation employing modern commercially available devices," Circuits, Systems, and Signal Processing, vol. 34, p. 3449-3469, 2015.
https://doi.org/10.1007/s00034-015-0015-7
32. W. Tangsrirat, "Dual-mode sinusoidal quadrature oscillator with single CCCTA and grounded capacitors," Journal of Microelectronics, Electronic Components and Materials, vol. 46, 130–135, 2016. http://ojs.midem-drustvo.si/index.php/InfMIDEM/article/view/245
33. S. B. Salem, A. B. Saied, D. S. Masmoudi, "High-performance current-controlled quadrature oscillator using an optimized CCII," Journal of Microelectronics, Electronic Components and Materials vol. 46, pp. 91–99, 2016. http://www.midem-drustvo.si/Journal%20papers/MIDEM_46(2016)2p91.pdf
34. K. Banerjee, D. Singh, S. K. Paul, "Single VDTA based resistorless quadrature oscillator," Analog Integrated Circuits and Signal Processing, vol. 100, pp. 495–500, 2019.
https://doi.org/10.1007/s10470-019-01480-4
35. W. Jaikla, S. Adhan, P. Suwanjan, M. Kumngern, "Current/voltage-controlled quadrature sinusoidal oscillators for phase sensitive detection using commercially available IC," Sensors, vol. 20, 1319, 2020.
https://doi.org/10.3390/s20051319
36. S. Gupta, T. S. Arora, "Design and experimentation of VDTA based oscillators using commercially available integrated circuits," Analog Integrated Circuits and Signal Processing, vol. 106, pp. 713–728, 2021.
https://doi.org/10.1007/s10470-020-01784-w

37. B. Linares-Barranco, A. Rodriguez-Vbquez, E. Sanchez-Sinencio, J. L. Huertas, "Generation, design and tuning of OTA-C high frequency sinusoidal oscillators," IEE Proceedings-Circuits, Devices and Systems, vol. 139, pp. 557-568, 1992, https://doi.org/10.1049/ip-g-2.1992.0086
38. S. Summart, C. Thongsopa, W. Jaikla, "OTA based current mode sinusoidal quadrature oscillator with non-interactive control," Przeglad Elektrotechniczny, vol. 88, pp. 14-17, 2012, http://pe.org.pl/articles/2012/7a/3.pdf
39. T. Thosdeekoraphat, C. Thongsopa, S. Summart, C. Seatiaw, "Second order current-mode quadrature oscillators using OTAs," Przeglad Elektrotechniczny, vol. 92, pp. 165-160, 2016. http://pe.org.pl/articles/2016/2/43.pdf
40. W. Tangsrirat, T. Pukkalanun, W. Surakampontorn, "CDBA-based universal biquad filter and quadrature oscillator," Active and Passive Electronic Components, vol. 2008, Article ID 247171 (6 pages), 2008. https://doi.org/10.1155/2008/247171
41. W. Tangsrirat, "Novel minimum-component universal filter and quadrature oscillator with electronic tuning property based on CCCDBAs," Indian Journal of Pure and Applied Physics, vol. 47, pp. 815-822, 2009. http://hdl.handle.net/123456789/6200
42. S. Maheshwari, J. Mohan, D. S. Chauhan, "High input impedance voltage-mode universal filter and quadrature oscillator," Journal of Circuits, Systems and Computers, vol. 19, pp. 1597-1607, 2010. https://doi.org/10.1142/S0218126610006943
43. J. Jin, C. Wang, "Current-mode universal filter and quadrature oscillator using CDTAs," Turkish Journal of Electrical Engineering and Computer Sciences, vol. 22, pp. 276–286, 2014. https://doi.org/10.3906/elk-1207-62
44. J. Jin, "Resistorless active SIMO universal filter and four-phase quadrature oscillator," Arabian Journal for Science and Engineering, vol. 39, pp. 3887-3894, 2014. https://doi.org/10.1007/s13369-014-0985-y
45. S. Tuntrakoon, M. Kumngern, R. Sotner, N. Herencsar, P. Suwanjan, W. Jaikla, "High input impedance voltage-mode universal filter and its modification as quadrature oscillator using VDDDAs," Indian Journal of Pure and Applied Physics, vol. 55, pp. 324–332, 2017. http://op.niscair.res.in/index.php/IJPAP/article/viewFile/14214/1241
46. M. Gupta, P. Dogra, T. S. Arora, "Novel current mode universal filter and dual-mode quadrature oscillator using VDCC and all grounded passive elements," Australian Journal of Electrical and Electronics Engineering, vol. 16, pp. 220-236, 2019. https://doi.org/10.1080/1448837X.2019.1648134
47. T. S. Arora, B. Rohil, S. Gupta, "Fully integrable/cascadable CM universal filter and CM quadrature oscillator using VDCC and only grounded passive elements," Journal of Circuits, Systems and Computers, vol. 28, 1950181 (36 pages), 2019. https://doi.org/10.1142/S0218126619501810
48. F. Yucel, E. Yuce, "Supplementary CCII based second-order universal filter and quadrature oscillators," AEU-International Journal of Electronics and Communications, vol. 118, 153138, 2020. https://doi.org/10.1016/j.aeue.2020.153138
49. W. Tangsrirat, T. Pukkalanun, O. Channumsin, "Single VDGA-based dual-mode multifunction biquadratic filter and quadrature sinusoidal oscillator," Journal of Microelectronics, Electronic Components and Materials, vol. 50, pp.125-136, 2020. https://doi.org/10.33180/InfMIDEM2020.205
50. M. Siripruchyanun, W. Jaikla, "Cascadable current-mode biquad filter and quadrature oscillator using DO-CCCIIs and OTA," Circuits, Systems, and Signal Processing, vol. 28, pp. 99-110, 2009. https://doi.org/10.1007/s00034-008-9072-5
51. W. Jaikla, M. Siripruchyanun, A. Lahiri, "Resistorless dual-mode quadrature sinusoidal oscillator using a single active building block," Microelectronics Journal, vol. 42, pp. 135–140, 2011, https://doi.org/10.1016/j.mejo.2010.08.017
52. M. Gupta, T. S. Arora, "Realization of current mode universal filter and a dual-mode single resistance-controlled quadrature oscillator employing VDCC and only grounded passive elements," Advances in Electrical and Electronic Engineering, vol. 15, pp. 833-845, 2017. https://doi.org/10.15598/aeee.v15i5.2397
53. M. Gupta, T. S. Arora, "Various applications of analog signal processing employing voltage differencing current conveyor and only grounded passive elements: a re-convertible approach," SN Applied Sciences, vol. 2, 2020. https://doi.org/10.1007/s42452-020-03379-6
54. H.-P. Chen, Y.-S. Hwang, Y.-T. Ku, S.-F. Wang, C.-H. Wu, "Voltage-mode universal biquadratic filter and quadrature oscillator using CFAs" IEICE Electronics Express, vol. 13, pp. 1–11, 2016. https://doi.org/10.1587/elex.13.20160510
55. Y. A. Li, "Electronically tunable current-mode biquadratic filter and four-phase quadrature oscillator," Microelectronics Journal, vol. 45, pp. 330–335, 2014, https://doi.org/10.1016/j.mejo.2013.12.005
56. M. Kumngern, E. Wareechol, P. Phasukkit, "Quadrature oscillator and universal filter based on translinear current conveyors," AEU-International Journal of Electronics and Communications, vol. 94, pp. 69–78, 2018, https://doi.org/10.1016/j.aeue.2018.06.044

57. M. Kumngern, F. Khateb, "Current-mode universal filter and quadrature oscillator using current controlled current follower transconductance amplifiers," Analog Integrated Circuits and Signal Processing, vol. 100, pp. 235–248, 2019, https://doi.org/10.1007/s10470-018-1345-8
58. https://www.maximintegrated.com/en/products/analog/analog-switches-multiplexers/MAX14689.html
59. S.-H. Tu, C.-M. Chang, J. N. Ross, M. N. S. Swamy, "Analytical synthesis of current-mode high-order single-ended-input OTA and equal-capacitor elliptic filter structures with the minimum number of components," IEEE Transactions on Circuits and Systems-I, vol. 54, pp. 2195-2210, 2007, https://doi.org/10.1109/TCSI.2007.905644
60. Texas Instruments, LM13700: Dual Operational Transconductance Amplifier with Linearizing Diodes and Buffers. URL http://www.ti.com/product/LM13700; 2015.
61. Texas Instruments, CD4016B: 4-channel analog switch, URL https://www.ti.com/product/CD4016B
62. R. Sotner, J. Jerabek, L. Langhammer, J. Polak, N. Herencsar, P. Prokop, J. Petrzela, W. Jaikla, "Comparison of two solutions of quadrature oscillators with linear control of frequency of oscillation employing modern commercially available devices," Circuits, Systems, and Signal Processing, vol. 34, pp. 3449-3469, 2015. https://doi.org/10.1007/s00034-015-0015-7

Arrived: 22. 06. 2021
Accepted: 02. 11. 2021