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CMOS Single Input Multiple Output Universal Biquad Filter Current-Mode Using Only OTAs

***Abstract**. This paper presents a new single-input multiple-output universal biquad filter in current-mode with only four operational transconductance amplifiers (OTAs) and two grounded capacitors. The proposed filter can be obtained all filtering functions, low-pass, high-pass, band-pass, band-stop and all-pass filter that the transfer functions of the filter can be selected by choosing appropriate current output without any component matching conditions. The natural frequency and quality factor of all filtering functions can be controlled electronically and orthogonally using the bias currents of transconductance amplifiers. The active and passive sensitivities of the filters are low. The proposed filter has been simulated using 0.18 µm CMOS process from TSMC. PSPICE simulation results are included to confirm workability of the proposed circuits.*

***Streszczenie.** W niniejszym artykule przedstawiono nowy uniwersalny filtr biquad z pojedynczym wejściem i wieloma wyjściami w trybie prądowym z zaledwie czterema wzmacniaczami transkonduktancyjnymi (OTA) i dwoma uziemionymi kondensatorami. W proponowanym filtrze można uzyskać wszystkie funkcje filtrowania, dolnoprzepustowy, górnoprzepustowy, pasmowoprzepustowy, pasmowy i wszechprzepustowy, dzięki czemu funkcje przenoszenia filtra można wybrać poprzez wybór odpowiedniego wyjścia prądowego bez żadnych warunków dopasowania komponentów . Naturalną częstotliwość i współczynnik jakości wszystkich funkcji filtrowania można kontrolować elektronicznie i ortogonalnie za pomocą prądów polaryzacji wzmacniaczy transkonduktancyjnych. Aktywna i pasywna czułość filtrów jest niska. Proponowany filtr został zasymulowany przy użyciu procesu CMOS 0,18 µm firmy TSMC. Zawarto wyniki symulacji PSPICE, aby potwierdzić wykonalność proponowanych obwodów. (**CMOS wielowyjściowy uniwersalny filtr dwukwadratowy prądowy wykorzystujący tylko OTA**)*

Keywords: biquad filter, current mode, operational transconductance amplifier.
Słowa kluczowe: filtr dwukwadratowy, CMOS, OTA.

Introduction

It is well known that the universal biquad filter is a very useful second-order function block for realizing high-order circuit functions within the single circuit filter that can be obtained multi-filtering functions such as low-pass (LP), high-pass (HP), band-pass (BP), band-stop (BS) and all-pass (AP) filters. Many universal biquad filter is designed by using high performance active devices such as operational amplifier (Op-Amp) and second generation current conveyor (CCII). Compared with the structures and performances between Op-Amp and CCII, CCII is simpler and easier to implementation which received considerable attention owing to the fact that their bandwidth, linearity and dynamic range performances are better than Op-Amp. Moreover, operational transconductance amplifier (OTA) is also high performance active devices and require no resistor which is highly suitable for integrated circuit (IC) implementation [1]. OTA is often used for universal biquad filter because it has some advantages in the circuit design such as electronic tuning capability, powerful ability to generate various circuits [2]. OTA can be easily connected in series to form a high-order filter because it has high-input impedance. Moreover, the transconductance gain (g_m) of OTA can be regulated by an outside electronically which is especially suitable for analog circuits.

The design of universal biquad filter has been interested by using only active devices that are more suitable for IC, high frequency operation and obtained multi-filtering functions. The active devices that have three characteristics; Op-Amp has been used firstly for the universal biquad filter using current-feedback operational amplifiers (CFOAs) which has been proposed in the past [3]-[7]. Later, OTA and CCII are proposed in [8]-[17] and [18]-[23], respectively with bipolar, complementary metal-oxide-semiconductor (CMOS) and BiCMOS technology that are good realization in commercial. The active devices using for universal biquad filter have been prepared by bipolar and CMOS technology, the CMOS technology is the most rapidly developing high-tech fabrication technique by silicon conductor [24]. Moreover, by considering the input and output terminals of universal biquad filters, these filters can be three classified as a single-input multiple-output (SIMO) filter [4], [10]-[13], [18], [22], multiple-input single-output (MISO) filter [3], [5]-[7], [9], [14]-[17], [20]-[21], [23] and a multiple-input multiple-output (MIMO) filter [8], [19]. The main advantage for SIMO is usually provided variant filtering functions by appropriately selecting the output signals when the input terminal is applied by a single signal after that the variant filtering functions can be obtained at its output terminals without changing any connections. On the other hand, The MISO and MIMO filters offer variant filtering functions by appropriately connecting the input signals, thus low active and passive component counts are normally possessed.

When the operation mode for universal biquad filter circuits have been considered, there are voltage-mode (VM) [3]-[10], [14], [16]-[17], [20], current-mode (CM) [11], [18]-[22] and mixed mode [12]-[13], [15], [23] which the circuits can be operated by all VM and CM. However, the operation mode circuits VM and CM have been prepared, the CM has the advantage such as wider bandwidth and larger dynamic range, better linearity and simplicity of implementation signal operations. Specifically, the universal biquad filter circuits based on only OTAs in [9]-[10], [14]-[17] are VM which the circuits have a drawbacks when VM is compared with CM. Beside the number of OTAs, the circuits is realized by a large number of CMOS that has been proposed in [9]-[11], [13]-[17]. Moreover, multiple-output OTA (MO-OTA) and OTA universal biquad filter have been proposed in [11] that CM proportional-block is used and [13] that can be operated mixed mode by selecting on-off the switch. The comparison between proposed circuit and some previous universal biquad filter is summarized in Table 1.

In this paper, advantages of SIMO universal biquad filter with single topology in CM using only active devices OTA is presented. The circuit will focus on the filter by CMOS technology that provides the filtering functions of LP, HP, BP, BS and AP filters into single topology, without changing any connections and also offering natural frequency ω_0 and quality factor Q of all filtering functions can be controlled electronically and orthogonally using the bias currents of transconductance amplifiers.

Table 1. Comparison of proposed filter with those of some previous universal biquad filters.

Circuits	Number of active elements	Number of resistor (R) & capacitor (C)	Offer five standard filters simultaneously	Orthogonal control for Q and ω_o	Offer electronically tunable for Q and ω_o	Type of filter	Operation mode
Proposed filters	4-OTA	2-C	Yes	Yes	Yes	SIMO	CM
Ref. [3]	4 CFOA	3-R & 2-C	Yes	Yes	No	MISO	VM
Ref. [4] Fig. 1 (a), (c), (d) Fig. 1 (b)	 4 CFOA 4 CFOA	 8-R & 2-C 9-R & 2-C	 Yes Yes	 Yes Yes	 No No	 SIMO SIMO	 VM VM
Ref. [5]	2 CFOA	2-R & 2-C	No	No	No	MISO	VM
Ref. [6]	4 CFOA	5-R & 2-C	Yes	Yes	No	MISO	VM
Ref. [7]	4 CFOA	5-R & 2-C	Yes	Yes	No	MISO	VM
Ref. [8]	3-OTA	2-C	Yes	Yes	Yes	MIMO	VM
Ref. [9]	6-OTA	2-C	Yes	Yes	Yes	MISO	VM
Ref. [10]	8-OTA	2-C	Yes	Yes	Yes	SIMO	VM
Ref. [11]	2-MO-OTA & 2-OTA	2-C	Yes	Yes	Yes	SIMO	CM
Ref. [12]	3-OTA	2-C	Yes	Yes	Yes	SIMO	Mixed
Ref. [13]	3-MO-OTA & 1-OTA	2-C	Yes	Yes	Yes	SIMO	Mixed
Ref. [14]	6-OTA	2-C	Yes	Yes	Yes	MISO	VM
Ref. [15]	5-OTA	2-C	Yes	Yes	Yes	MISO	Mixed
Ref. [16]	6-OTA	2-R & 2-C	Yes	Yes	Yes	MISO	VM
Ref. [17]	5-OTA	2-C	Yes	Yes	Yes	MISO	VM
Ref. [18] Fig. 2	 3-CCII	 2-R & 2-C	 No	 No	 No	 SIMO	 CM
Ref. [19]	1-MO-CCII & 1-CCII	2-R & 2-C	Yes	No	No	MIMO	CM
Ref. [20]	3-CCII 3-CCII	1-R & 2-C 4-R & 2-C	Yes Yes	No No	No No	MISO MISO	CM VM
Ref. [21]	1-CCII & 1-CCIII	2-R & 2-C	Yes	No	No	MISO	CM
Ref. [22]	1-MO-CCII & 1-DVCC	3-R & 2-C	Yes	Yes	No	SIMO	CM
Ref. [23]	4-CCII	4-R & 2-C	Yes	Yes	No	MISO	Mixed

Note: Note: CFOA = current-feedback operational amplifier, CCII = second generation current conveyor, MO-CCII = multiple output second generation current conveyor, CCIII = third generation current conveyor, OTA = operational transconductance amplifier, MO-OTA = multiple output operational transconductance amplifier, DVCC = differential voltage current conveyor, SIMO = single-input multiple-output, MISO = multiple-input single-output, MIMO = multiple-input multiple-output, VM = voltage mode, CM = current mode, Mixed = voltage mode and current mode

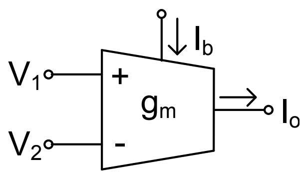

Fig.1. The circuit symbol of OTA

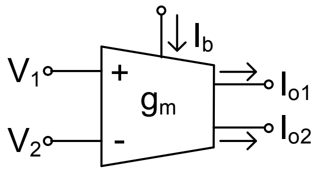

Fig.2. The circuit symbol of DO-OTA

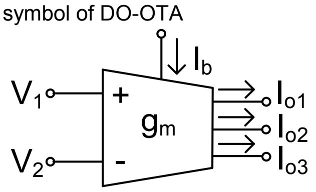

Fig.3. The circuit symbol of MO-OTA

OTA, dual-output OTA and multiple-output OTA

OTA consists of two voltage input ports and one output port that is current output [9]. Thus, it can be modified by more than one output that is dual-output OTA (DO-OTA) [25] or multiple-output OTA (MO-OTA). The circuit symbols of OTA, DO-OTA and MO-OTA are shown in Fig. 1 - Fig. 3.

The OTA, DO-OTA and MO-OTA characteristics can be expressed by equation (1) – (3), respectively.

(1) $$I_o = g_m\left(V_1\text{-}V_2\right)$$

(2) $$I_{o1} = I_{o2} = g_m\left(V_1\text{-}V_2\right)$$

(3) $$I_{o1} = I_{o2} = I_{o3} = g_m\left(V_1\text{-}V_2\right)$$

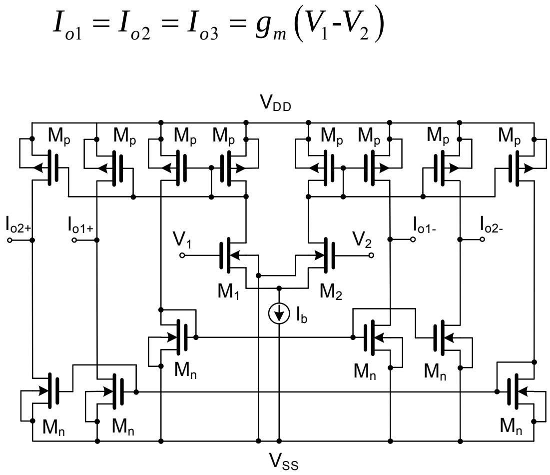

Fig.4. The schematic of MO-OTA [25]

However, by using CMOS technology, the schematic of MO-OTA is shown in Fig. 4. The transconductance g_m is written as follow;

(4) $$g_m = \sqrt{\mu_n C_{ox}(W/L)I_b}$$

Where: μ_n is mobility of carrier in the channel, C_{ox} is the gate-oxide capacitance per unit area and I_b is bias current of OTA. *W* and *L* are the effective channels width and length of MOS, respectively. Then, g_m can be electronically tuned and found through the biasing current I_b [25].

Proposed circuit

Fig. 5 shows the proposed CMOS universal biquad filter circuit with single-input multiple-output. It can be seen that the filter circuit is constructed with only active device OTAs and passive devices, respectively, with four OTAs that are one MO-OTA, two DO-OTA and one single-ended OTA and two grounded capacitors. Then, the circuit is beneficial to IC implementation. From Fig. 5 that by using nodal circuit analysis, the current transfer functions of all filtering can be selected by choosing appropriate current output that can be expressed as

(5) $$\frac{I_{o1}}{I_{in}} = \frac{g_{m1}g_{m3}}{s^2C_1C_2 + sC_2g_{m2} + g_{m1}g_{m3}}$$

(6) $$\frac{I_{o2}}{I_{in}} = \frac{-sC_2g_{m2}}{s^2C_1C_2 + sC_2g_{m2} + g_{m1}g_{m3}}$$

(7) $$\frac{I_{o3}}{I_{in}} = \frac{s^2C_1C_2}{s^2C_1C_2 + sC_2g_{m2} + g_{m1}g_{m3}}$$

(8) $$\frac{I_{o1}+I_{o3}}{I_{in}} = \frac{s^2C_1C_2 + g_{m1}g_{m3}}{s^2C_1C_2 + sC_2g_{m2} + g_{m1}g_{m3}}$$

(9) $$\frac{I_{o1}+I_{o2}+I_{o3}}{I_{in}} = \frac{s^2C_1C_2 - sC_2g_{m2} + g_{m1}g_{m3}}{s^2C_1C_2 + sC_2g_{m2} + g_{m1}g_{m3}}$$

Thus, the circuit realises LP signal at I_{o1}, BP signal at I_{o2} and HP signal at I_{o3}. Continuously, BS and AP signals can be obtained from the current output by choosing, respectively, at I_{o1} and I_{o3} and I_{o1}, I_{o2}, and I_{o3}. Therefore, the natural frequency ω_o and quality factor *Q* are given by

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

(11) $$Q = \frac{1}{g_{m2}}\sqrt{\frac{g_{m1}g_{m3}C_1}{C_2}}$$

Letting, $g_m = g_{m1} = g_{m3}$ and $C = C_1 = C_2$, the circuit parameters are simplified to

(12) $$\omega_o = \frac{g_m}{C}$$

(13) $$Q = \frac{g_m}{g_{m2}}$$

From equation (12) and (13), the parameter ω_o can be set by transconductance g_m and parameter *Q* can be set by transconductance g_{m2} without disturbing ω_o. Thus, the proposed biquadratic filter has orthogonal controlling capability for the circuit parameters ω_o and *Q*. It can be seen that the parameter ω_o can also be controlled electronically by the transconductance g_m through adjusting the bias current I_b of OTAs. Moreover, all of five standard filtering functions of the proposed filter can easily be realized by choosing suitable outputs which the circuit requires no component matching condition.

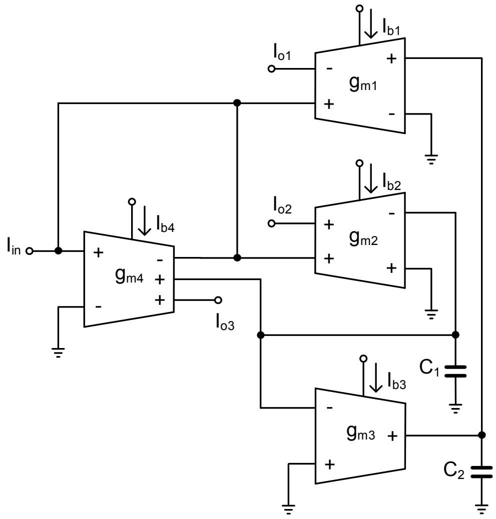

Fig.5. Proposed CMOS universal biquad filter with single-input multiple-output

Non-ideality analysis

The parasitic effects of non-ideality behaviour of OTA on the filter performances have been investigated. The transconductance g_{mn} of OTA with non-ideality can be written as [26]

(14) $$g_{mn} = \frac{g_m\omega_g}{s+\omega_g} \cong g_m(1-\mu s)$$

Where ω_g denotes the first-order pole of OTA and $\mu = 1/\omega_g$.

The circuit transfer functions in Fig. 5 can be reanalysed by equation (14). Thus, the denominator of transfer functions becomes

(15) $$\begin{aligned} D(s) &\cong s^2C_1C_2(1-g_{m2}\mu_2/C_1) \\ &+ sC_2g_{m2}\{1-g_{m1}g_{m3}(\mu_1+\mu_3)/C_2g_{m2}\} \\ &+ g_{m1}g_{m3} \end{aligned}$$

From equation (15), non-ideality behaviour of OTA will affect the circuit characteristics which departs from the ideal value. The effect of parasitic parameters of OTA can be made negligible by satisfying the following conditions:

(16) $$\begin{cases} g_{m2}\mu_2/C_1 \ll 1 \\ g_{m1}g_{m3}(\mu_1+\mu_3)/C_2g_{m2} \ll 1 \end{cases}$$

Beside the effect of the deviation of the active and passive components, the sensitivities of the filter parameters are calculated as follows:

(17) $$S_{g_{m1}}^{\omega_o} = S_{g_{m3}}^{\omega_o} = -S_{C_1}^{\omega_o} = -S_{C_2}^{\omega_o} = 0.5$$

(18) $$S_{g_{m1}}^{Q} = S_{g_{m3}}^{Q} = S_{C_1}^{Q} = -S_{C_2}^{Q} = 0.5$$

(19) $$S_{g_{m2}}^{Q} = -1$$

It is noted that the proposed filter offer low active and passive sensitivities by not more than unity in magnitude.

Simulation results

The proposed CMOS universal biquad filter is verified by the simulation from PSPICE simulators. All MOS transistors in Fig. 4 are used for OTA, DO-OTA and MO-OTA and will be designed by 0.18 μm TSMC CMOS parameters [27] which the aspect ratio for all nMOS and pMOS transistors are shown in Table 2. The interrelated parameters for using in this paper and summarized performance of OTAs are shown in Table 3. The capacitor C_1 and C_2 were given a value of 59 pF. Fig. 6 shows the simulated frequency responses of LP, BP, HP and BS filters when the bias current I_{b1}, I_{b2}, I_{b3} and I_{b4} were chosen by 50 µA that are 371 µS for all transconductance g_{m1}, g_{m2}, g_{m3} and g_{m4}.

Table 2. MOS Transistor aspect ratios used for Fig. 4

MOS Transistor	W/L(μm/μm)
M_n	8/0.8
M_p	25/0.8
M_1, M_2	10/0.8

Table 3. Interrelated parameters and summarized performances of OTAs in Fig. 5

Parameters	Values
Technology	0.18 μm
Supply voltage (V)	±0.9 V
Transconductance (g_m) (I_b = 2 - 300 μA)	74-908 µS
-3 dB bandwidth (I_b = 50 A)	162 MHz
R_o//C_o	260 kΩ//9.44 fF
Power consumption (I_b = 50 μA)	1.4 mW

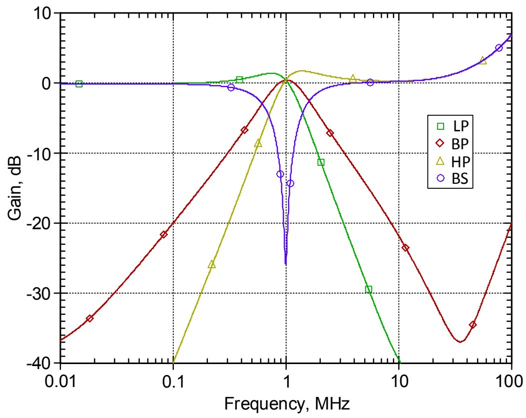

Fig.6. Simulated LP, BP, HP and BS of the proposed filter

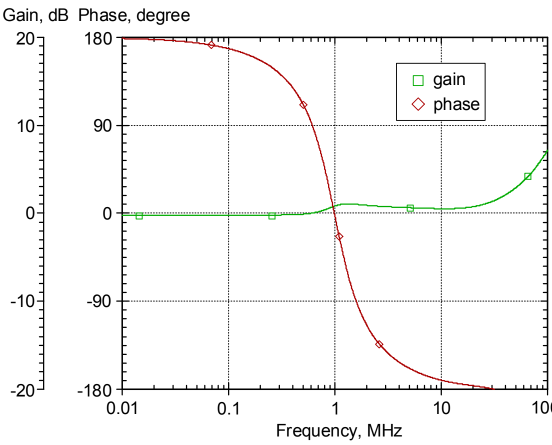

Fig.7. Simulated gain and phase responses of AP filter

Fig. 7 shows the simulated gain and phase responses of AP filter. From Figs. 6 and 7, it was confirmed that LP, BP, HP, BS and AP filters can be obtained by choosing appropriate current output without any component matching conditions. Fig. 8 shows the simulated BP response when the bias current I_{b1} and I_{b3} are varied to confirm equation (10) and (12). It can be seen that the natural frequency ω_0 has been varied by the transconductance g_{m1} and g_{m3}. In this case, the bias current I_{b2} and I_{b4} are varied the same values of the bias current I_{b1} and I_{b3}.

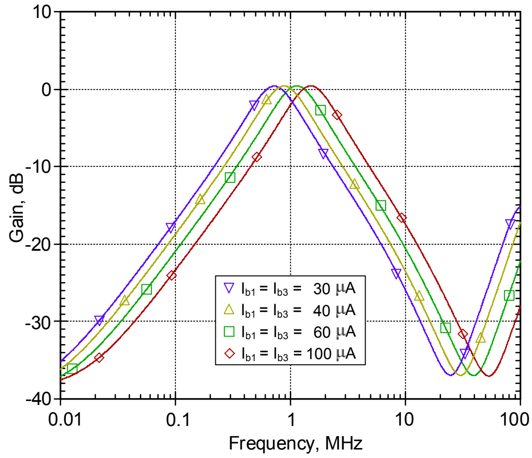

Fig.8. Simulated BP response for Ib_1 and Ib_3 are varied

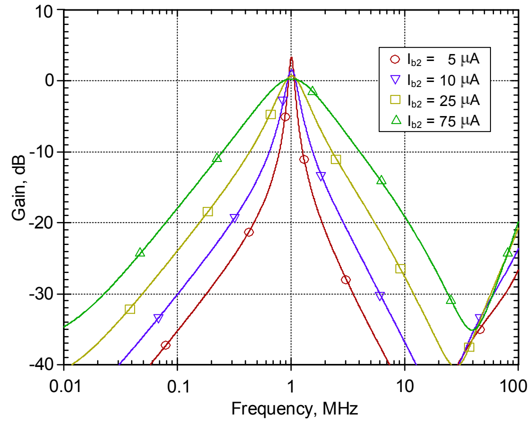

Fig.9. Simulated frequency responses of BP filter when Ib_2 was varied.

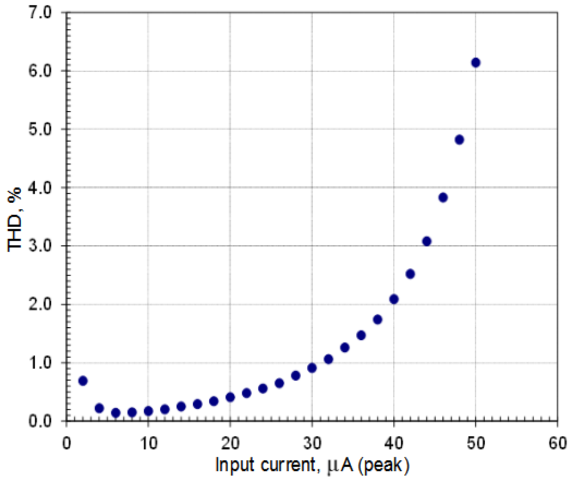

Fig.10. THD variations of the LP filter on input amplitude signal

In addition, to confirm equation (11) and (13), Fig. 9 shows the simulated responses of BP filter when the bias current I_{b2} was varied but I_{b1}, I_{b3} and I_{b4} were chosen by 50 µA. It was confirmed that the parameter *Q* can be controlled by adjusting g_{m2} via I_{b2}. Moreover, the linearity of the proposed filter is tested by selecting LP filter functional that the sinusoidal input current 100 kHz and 10 harmonics have been used. Then, the variations of the output percentage of total harmonic distortion (THD) for LP filter is shown in Fig. 10. The THD was about 1.06 % when the input current amplitude was 32 µA (peak) and will be increased linearity to 6.14 % when the input current amplitude was 50 µA (peak). The power consumption of the proposed circuit was 1.4 mW.

Conclusions

This paper presents a new CMOS single-input multiple-output universal biquad filter in current-mode using only active device with four OTAs and passive device with two grounded capacitors. The proposed filter provides LP, BP, HP, BS and AP filter responses that the transfer functions of the filter can be selected by choosing appropriate current output without any component matching conditions. Also the natural frequency ω_0 and quality factor Q of all filtering functions can be controlled electronically and orthogonally using the bias currents of transconductance amplifiers. The sensitivities of the proposed filter are low. The effectiveness and the performances of the proposed circuit have been confirmed by PSPICE simulation that are workability.

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