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# New Current-mode Three-Inputs One-output Multifunction Filter with Independent Tune of $\omega_0$ and Q

***Abstract****. In this study, a three-inputs single-output current-mode analog biquadratic filter, based on second generation current controlled current conveyor (CCCII) is presented. The proposed filter uses four CCCIIs and two grounded capacitors without any external resistors, which is well suited for integrated circuit implementation. The circuit gives five standard transfer functions, namely, lowpass, highpass, bandpass, notch and allpass filters with independent control of quality factor and pole frequency by electronic method. Each function response can be selected by suitably selecting input signals with digital method. The filter does not require double input current signal. Moreover, the circuit possess high output impedance which would be an ideal choice for current-mode cascading. The PSPICE simulation results, using CMOS CCCII in 0.25μm TSMC CMOS technology, are included to verify the workability of the proposed filter. The given results agree well with the theoretical anticipation.*

***Streszczenie.*** *Opisano trójwejściowy prądowy bikwadratowy filtr analogowy bazujący na drugiej generacji układzie CCCII (current controlled current conveyor).Opisany układ składa się z czterech CCCII i dwóch uziemionych kondensatorów bez potrzeby używania zewnętrznych rezystorów. Układ pozwala na realizację wszystkich rodzajów filtrów z niezależnym ustawieniem dobroci Q i częstotliwości odcięcia.* ***Nowy, trójwejściowy wielofunkcyjny filtr analogowy z niezależnym strojeniem dobroci i częstotliwości****.*

**Keywords:** current-mode; CCCII, filter, integrated circuit, analog circuit.
**Słowa kluczowe:** filtr analogowy, układ CCCII, obwód scalony.

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## Introduction

Over the past two decades, a number of analog circuit based on current-mode approach have been developed. It is mentioned that the current-mode circuits give the potential advantages such as higher slew-rate, greater linearity, wider dynamic range, inherently wide bandwidth, simpler circuitry and lower power consumption [1-2] . It is found that number of research papers in analog circuit design have been published relative to the implementation of current-mode circuits [3-5]. An analog active filter is one of the standard research topics in current-mode circuit design. The analog filter is one of the important requirements in electrical and electronic applications, widely used for continuous-time analog signal processing. It is generally used in many fields, such as communications, measurement, and instrumentation, and control systems [6-7]. Especially, the filters which provides several functions in the same topology, namely, universal filter or multifunction filter, have been receiving considerable attention. Considering the number of input and output ports, these filters can be classified into three categories: a single-input, multiple-output (SIMO) type, a multiple-input, single-output (MISO) type [8] and a multiple-input, multiple-output (MIMO) type [9]. One of most popular analog current-mode filters is a multiple-input single-output biquadratic filter (MISO) which different output filter functions can be realized simply by different combinations of switching on or off the input currents where the selection can be done digitally using a microcontroller or microcomputer. With growing interest in design of current-mode filters, more attention is being paid to the filters which have the high-output impedance because they make them easy to drive loads and they facilitate cascading without using a buffering device [9-10].

Table 1. Comparison between various MISOs

| Ref | Active element | No. of active element | No. of R+C | Electronic control | Independent tune of $\omega_0$ and Q | Requiring double input | Matching Condition | High output impedance |
|---|---|---|---|---|---|---|---|---|
| [8] | ICCII | 3 | 2+2 | No | No | No | No | Yes |
| [9] | CCII | 3 | 3+2 | No | Yes | No | No | Yes |
| [16] | CCII | 1 | 2+2 | No | No | No | Yes | No |
| [17] | CCII | 1 | 2+2 | No | No | No | Yes | Yes |
| [18] | CCII | 2 | 3+2 | No | Yes | Yes | Yes | Yes |
| [19] | CCII | 6 | 6+2 | No | Yes | No | Yes | Yes |
| [20] | FDCCI | 1 | 3+2 | No | Yes | No | Yes | Yes |
| [21] | MO-CCII & MO-CCCA | 3 | 2+2 | Yes | Yes | No | No | Yes |
| [22] | OTA | 4 | 0+2 | Yes | No | No | Yes | Yes |
| [23] | CDTA | 3 | 0+2 | Yes | No | No | No | Yes |
| [24] | CDTA | 2 | 0+2 | Yes | No | Yes | No | Yes |
| [25] | CDTA | 4 | 2+2 | Yes | Yes | No | No | Yes |
| [26] | CDBA | 3 | 2+2 | No | No | Yes | No | Yes |
| [27] | CCCDTA | 1 | 0+2 | Yes | No | Yes | No | Yes |
| [28] | MO-CCCCTA | 1 | 0+2 | Yes | No | No | No | Yes |
| [29] | MO-CCCCTA | 2 | 0+2 | Yes | No | No | No | Yes |
| [30] | DVCCTA | 1 | 1+2 | Yes | No | No | No | Yes |
| [31] | G-CCCII | 2 | 0+2 | Yes | Yes | Yes | No | Yes |
| [32] | CCCII | 2 | 0+2 | Yes | No | No | No | Yes |
| [33] | CCCII | 5 | 0+2 | Yes | Yes | No | Yes | Yes |
| Proposed filter | CCCII | 4 | 0+2 | Yes | Yes | No | No | Yes |

The CCII is a reported active component, especially suitable for a class of analog signal processing [11]. This device can operate in both current and voltage-modes, providing flexibility and enabling a variety of circuit designs. In addition, it can offer advantageous features such as high-slew rate, higher speed, wide bandwidth and simple implementation [11-12]. However, the CCII can not control the parasitic resistance at X ($R_x$) port so when it is used in some circuits, it must unavoidably require some external passive components, especially the resistors. This makes it not appropriate for IC implementation due to occupying more chip area, high power dissipation and without electronic controllability. On the other hand, the introduced second-generation current-controlled conveyor (CCCII) [13] has the advantage of electronic adjustability over the CCII. Also, the use of dual-output current conveyor is found to be useful in the derivation of current-mode single input three output filters using a reduced number of active components [14-15].

Numerous techniques using active building block for designing the MISO current-mode filters have been developed in the past two decades [8-9, 16-34]. These MISO current-mode filters are based on inverting current conveyor (ICCII) [8], current conveyor (CCII) [9, 16-19], inverting current conveyor (ICCII) [20], CCII and current controlled current amplifier (CCCA) [21], OTA [22], current differencing transconductance amplifier (CDTA) [23-25], current differencing buffered amplifier (CDBA) [26], Current-controlled CDTA (CCCDTA) [27], current controlled current conveyor transconductance amplifier (CCCCTA) [28-29], differential voltage current conveyor transconductance amplifire (DVCCTA) [30], gain-controllable current controlled current conveyor (G-CCCII) [31], current controlled current conveyors (CCCII) [32-33], and current follower tansconductance amplifier [34]. The advantages of the proposed MISO current-mode filter are compared with several previous current-mode MISO current-mode filters which the results are shown in Table 1.

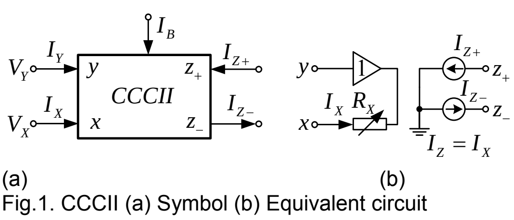
A new configuration capable of realizing current-mode lowpass, highpass, bandpass, notch and allpass filters with three inputs and one output using 4 CCCIIs and two capacitors is presented in this paper. The paper is organized as follows. In section 2, the characteristics of CMOS CCCII and proposed filter with either an ideal or a non-ideal active element are presented. The simulation results and their evaluations are given in detail in section 3. Finally, section 4 concludes the paper.

## Theory and Principle

### *Basic Concept of CCCII*

The circuit symbol and equivalent of the CCCII are shown respectively in Fig. 1(a) and (b), where y and x are the input terminals, and z is the output terminal. In general, CCCII can contain an arbitrary number of z terminals; provide both directions of currents $I_z$. As an example, the symbol and the equivalent circuit of the CCCII with a pair of z+ and z- terminals are illustrated in Fig. 1. The characteristics of ideal CCCII can be described by:

(1) $$\begin{bmatrix} I_y \\ V_x \\ I_z \end{bmatrix} = \begin{bmatrix} 0 & 0 & 0 \\ 1 & R_x & 0 \\ 0 & \pm 1 & 0 \end{bmatrix} \begin{bmatrix} V_y \\ I_x \\ V_z \end{bmatrix}.$$



(a) (b)

Fig.1. CCCII (a) Symbol (b) Equivalent circuit

If the CCCII is realized using CMOS technology, parasitic resistance at x terminal ($R_x$) can be written as

(2) $$R_X = \sqrt{\frac{1}{kI_B}};\ k = 8\mu_n C_{ox}\left(\frac{W}{L}\right)_{10-11} = 8\mu_n C_{ox}\left(\frac{W}{L}\right)_{12-13}.$$

Here k is the physical transconductance parameter of the MOS transistor. $I_B$ is the bias current used to control the intrinsic resistance at x port. The internal construction of CMOS CCCII is shown in Fig. 2.

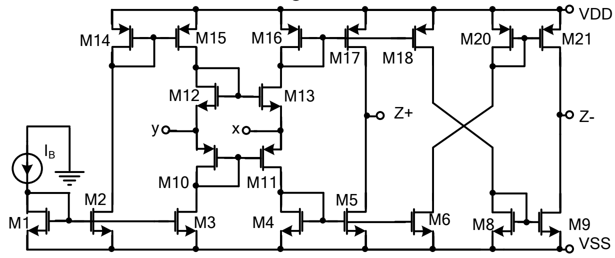


Fig.2. Internal construction of CCCII

### *Proposed MISO Current-Mode Biquad Filter*

The proposed current-mode filter is shown in Fig. 3. It consists of 4 CCCIIs and 2 grounded capacitors. The output current $I_{Out}$ with high impedance is flowed out from z terminal of CCCII2. It also found that the proposed filter does not require the summing of input current at output node. By routine analysis of the circuit in Fig. 3, the output current can be obtained to be

(3) $$I_{Out} = \frac{R_{x3}}{R_{x2}}\left(\frac{I_{in2}s^2C_1C_2R_{x1}R_{x4} + I_{in1}sC_2R_{x4} + I_{in3}}{s^2C_1C_2R_{x1}R_{x4} + s\dfrac{C_2R_{x3}R_{x4}}{R_{x2}} + 1}\right).$$

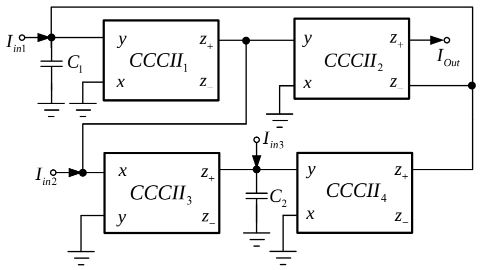


Fig.3. Proposed filter

Table 2. The $I_{in1}$, $I_{in2}$ and $I_{in3}$ values selection for each filter function response

| Filter Responses | Input selections | | |
|---|---|---|---|
| $I_{Out}$ | $I_{in1}$ | $I_{in2}$ | $I_{in3}$ |
| BP | 1 | 0 | 0 |
| HP | 0 | 1 | 0 |
| BR | 0 | 1 | 1 |
| AP | -1 | 1 | 1 |
| LP | 0 | 0 | 1 |

Depending on the current status in Table 2 of $I_{in1}$, $I_{in2}$, and $I_{in3}$ in the numerator of Eq. (3), one of the five filter functions is obtained as the $2^{nd}$–order network without requirement of double input current signal(s). Moreover, it is found in Table 2 that each function response can be selected by digital method. The realization of the digital selection can also be based on the already proposed solution [35]. The pole frequency ($\omega_0$) and quality factor (Q) of each filter response can be expressed to be

(4) $$\omega_0 = \sqrt{\frac{1}{C_1C_2R_{x1}R_{x4}}} \text{ and } Q = \frac{R_{x2}}{R_{x3}}\sqrt{\frac{C_1R_{x1}}{C_2R_{x4}}}.$$

If $R_{xi}=(1/kI_{Bi})^{0.5}$ as written in Eq. (2), the pole frequency, and quality factor of the proposed filter are written:

(5) $\omega_0 = \sqrt{\frac{k\left(I_{B1}I_{B4}\right)^{\frac{1}{2}}}{C_1C_2}}$ and $Q = \sqrt{\frac{C_1I_{B3}\left(I_{B4}\right)^{\frac{1}{2}}}{C_2I_{B2}\left(I_{B1}\right)^{\frac{1}{2}}}}$ .

From Eq. (5), it is found that the quality factor can be adjusted independently from the pole frequency by varying $I_{B2}$ or $I_{B3}$. Another advantage of the proposed circuit is that the high Q can be obtained by setting $I_{B3}$ more greater than $I_{B2}$ without effecting pole frequency. Furthermore, it can be remarked that if $I_{B1}=I_{B4}=I_B$, this can be achieved by using current mirror copying the current $I_B$ to terminals $I_{B1}$ and $I_{B4}$ of $CCCII_1$ and $CCCII_2$, respectively. The pole frequency and quality factor can be expressed as

(6) $\omega_0 = \sqrt{\frac{kI_B}{C_1C_2}}$ and $Q_0 = \sqrt{\frac{I_{B3}C_1}{I_{B2}C_2}}$ .

From Eq. (6), it should be remarked that the pole frequency can be electronically adjusted by $I_B$ without disturbing the quality factor

***Circuit Sensitivities***

The sensitivities of the proposed circuit can be found as

(7) $S_{I_{B1}}^{\omega_0} = S_{I_{B4}}^{\omega_0} = \frac{1}{4};\ S_k^{\omega_0} = \frac{1}{2}; S_{C_1}^{\omega_0} = S_{C_2}^{\omega_0} = -\frac{1}{2}$ ,

and

(8) $S_{C_1}^{Q_0} = S_{I_{B3}}^{Q_0} = \frac{1}{2};\ S_{C_2}^{Q_0} = S_{I_{B2}}^{Q_0} = -\frac{1}{2}; S_{I_{B4}}^{Q_0} = \frac{1}{4}; S_{I_{B1}}^{Q_0} = -\frac{1}{4}$ .

Therefore, all the active and passive sensitivities are equal or less than unity in magnitude.

***Analysis of Non-ideal Case***

For non-ideal case, the CCCII can be respectively characterized with the following equations,

(9) $I_Y = 0, V_X = \beta V_Y + R_X I_X$ , $I_Z = \alpha I_X$ .

In the case of non-idea and reanalysis of proposed filter circuit in Fig. 2, it yields the output current as

(10) $$I_{Out} = \frac{\frac{\beta_2\alpha_2R_{x3}}{R_{x2}}\left(\frac{s^2C_1C_2R_{x4}R_{x1}}{\beta_1\alpha_1}I_{in2} + I_{in1}sC_2R_{x4} + \beta_4\alpha_4I_{in3}\right)}{\frac{s^2C_1C_2R_{x4}R_{x1}}{\beta_1\alpha_1} + s\frac{\beta_2\alpha_2C_2R_{x3}R_{x4}}{R_{x2}} + \beta_4\alpha_3\alpha_4}.$$

In this case, the $\omega_0$ and Q are changed to

(11) $\omega_0 = \sqrt{\frac{\beta_1\beta_4\alpha_1\alpha_4\alpha_3}{C_1C_2R_{x1}R_{x4}}}$ and $Q = \frac{R_{x2}}{\beta_1\beta_2\alpha_1\alpha_2R_{x3}}\sqrt{\frac{\beta_1\beta_4\alpha_1\alpha_4\alpha_3C_1R_{x1}}{C_2R_{x4}}}$ .

Practically, α and β originate from intrinsic resistances and stray capacitances in the active elements. These errors affect the sensitivity to temperature and high frequency response of the proposed circuit. From Eqs. (10) and (11), it is found that the current and voltage gains depend on the temperature and frequency variations, then the CCCII should be designed to achieve these errors as low as possible.

**Simulation Results**

The performances of proposed filter are verified using PSpice simulation. The CCCII is realized as shown in Fig. 2. The PMOS and NMOS transistors have been simulated by respectively using the parameters of a 0.25μm TSMC CMOS technology [36]. The aspect ratios of PMOS and NMOS transistor are listed in Table 3. The circuit was biased with ±1.25V supply voltages, $C_1=C_2=0.1nF$, $I_{B1}=I_{B2}=I_{B3}=I_{B4}=50\mu A$ are chosen. It yields the pole frequency of 2MHz. The results shown in Fig. 4 are the gain and phase responses of the proposed filter obtained from the filter in Fig. 3. It is clearly seen that the proposed filter can provide low-pass, high-pass, band-pass, band-reject and all-pass functions, dependent on digital selection as shown in Table 2, without modifying circuit topology.

Table 3. Dimensions of MOS transistors

| Transistor | W (μm) | L (μm) |
|---|---|---|
| M1-M9 | 5 | 0.5 |
| M10-M11 | 16 | 0.25 |
| M12-M13 | 8 | 0.25 |
| M14-M16, M18-21 | 15 | 0.5 |

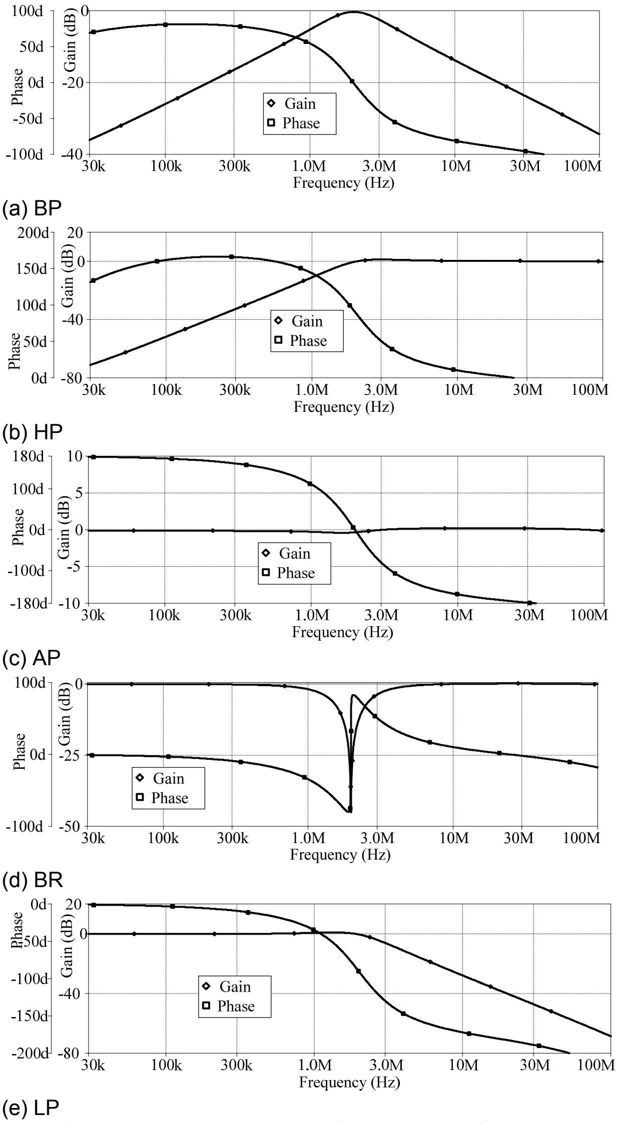


Fig.4. Gain and phase responses of the proposed filter

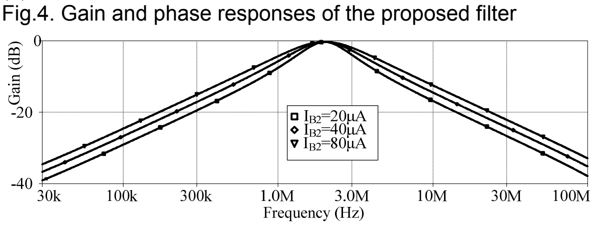


Fig.5. Band-pass responses at different values of $I_{B2}$

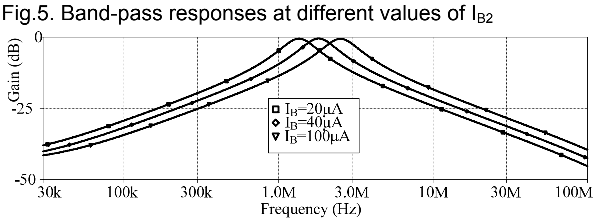


Fig.6. Band-pass responses at different values of $I_B$

Fig. 5 displays gain responses of band-pass function for different $I_{B2}$ values. It is shown that the quality factor can be adjusted by $I_{B2}$, as depicted in Eq. (5) without affecting the pole frequency. Fig. 6 shows the gain responses of the band-pass function while setting $I_B$ to 20μA, 40μA, and 100μA, respectively. This result shows that the pole frequency can be adjusted without affecting the quality factor, as described in Eq. (6).

## Conclusions

The three-inputs single-output biquadratic filter performing completely standard functions: low-pass, high-pass, band-pass, band-reject and all-pass functions, based on current controlled current conveyor (CCCII). The features of the circuit are that: (i) the quality factor and pole frequency can be electronically/independently tuned via the input bias current, (ii) the circuit uses 4 CCCIIs and 2 grounded capacitors without external any resistors which is very suitable to further develop into an integrated circuit, (iii) the filter does not require double input current signal, (iv) each function response can be selected by suitably selecting input signals with digital method, (v) the circuit possess high output impedance which would be an ideal choice for current-mode cascading. The non-ideal analysis of the proposed circuit has been carried out and simulation results using PSpice have confirmed its workability.

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