# Electronically Tunable Single-Input Multi-Output Current-Mode Biquad Filter Suitable for Easy Cascading

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## ABSTRACT

This paper presents a new current-mode (CM) multi-function filter with one input and three outputs. The filter uses only three multi-output inverting second generation current conveyors (ICCIIs), two grounded capacitors and two MOS resistors. Without using any external passive elements, the proposed circuit can simultaneously realize lowpass (LP), bandpass (BP) and highpass (HP) responses without any matching or cancellation conditions, all at high impedance outputs which is important for easy cascading in CM operation. The bandstop (BS) and allpass (AP) responses can be obtained by connecting appropriate output currents directly without using additional active elements. The parameters $\omega_o$ and Q, can be electronically tuned by adjusting the bias voltages of the MOS resistances. The proposed circuit enjoys low sensitivities.

**Keywords:** Current-Mode, Biquad Filters, ICCII, MOS Resistance, Electronically Tuning

## مرشح من الدرجة الثانية احادي المدخل و متعدد المخارج يعمل في طور التيار ممكن ضبطه الكترونيا و ملائم للربط على التوالي

**الخلاصة**

هذا البحث يقدم شكلا جديدا من مرشح متنوع الدوال يعمل في طور التيار له مدخل واحد مع ثلاثة مخارج. يستخدم المرشح فقط ثلاثة من الدوائر الفعالة من نوع (الجيل الثانى من ناقلات التيار العاكسة ICCII,) ذات المخارج المتعددة مع مكثفين ارضيين و مقاومتين مصنوعتين من ترانزستورات الـMOS. من دون استخدام اية عناصر خارجية غير فعالة يمكن للدائرة المقدمة ان يستجيب لثلاثة انواع من المرشحات وهي مرشح امرار ترددات واطئة (lowpass) و مرشح امرار ترددات نطاقي (bandpass) و مرشح امرار ترددات عالية (highpass) في ان واحد دون اللجوء الى شروط التوليف او الحذف و كلها عبر مخارج ذات ممانعات عالية و التي هي مهمة في حالات الربط على التوالي للدوائر العاملة في طور التيار. و اما بالنسبة لاستجابة المرشح من نوع امرار كلي (allpass) و مانع نطاقي (bandstop) فيمكن تكوينهما بسهولة بربط التيارات الخارجة انفة الذكر و المناسبة لكل واحد

منهمـا مباشـرة دون اسـتخدام ايـة عناصـر فعالـة اضـافية. يمكـن ضـبط معـاملي المرشـح و همـا التـردد الوسـطي (central frequency, $\omega_o$) و عامـل الجودة(quality factor, Q) الكترونيـا و ذلك بواسـطة ضـبط فولتيـة بوابـة ترانزسـتورات الـMOS المكونـة للمقاومتين المستخدمتين. يتمتـع المرشـح بحساسـية واطئة.

## INTRODUCTION

In electrical engineering applications, an analog filter is an important block that is widely used for continuous-time signal processing. It can be found in many fields for example, communication, measurement, instrumentation and control systems. One of the most popular analog filters is the universal biquadratic filter as it can provide several functions [1]. Recently the research activities have trended to the development of current-mode (CM) filters since they offer several potential advantages such as wider bandwidth, better linearity, wider dynamic range and simplicity of signal operation compared with their voltage-mode (VM) counterparts [2]. Therefore, a number of multifunction CM filters based on CM active elements have been presented [1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11]. Multifunction filters are able to achieve more than one basic filter function simultaneously with the same topology. They therefore bring versatility, simplicity and cost reduction to the integrated circuit manufacturer. Second-generation current conveyors (CCIIs) have been found very useful in filtering applications. However, most of the CCII-based circuits presented in the literature suffer from a lack of electronic tunability [2, 3].

For CM circuits, low input impedance and/or high output impedance is advantageous from cascadability point of view. For certain filters in which output signal is obtained on a passive element additional active elements will be needed to sense the output signal [12]. In addition, for cascadability to obtain higher order filters the structure should exhibit high output resistance.

For the cases where power consumption is an important parameter, the number of active elements employed will be important. The circuit in [4] employs five active elements with floating resistors. The CDTA-based filter in [5] realizes simultaneously two responses in which one of the two outputs flows through the grounded capacitor. The CFTA-based filter in [6] realizes lowpass (LP), bandpass (BP) and highpass (HP) responses in which the BP and HP outputs flow through the grounded capacitors.

On the other hand by using the second generation current controlled conveyor (CCCII) introduced by Fabre and others [7], current conveyor applications have been extended to the domain of electronically tunable functions. However, only bipolar transistor (BJT) realization of the CCCII can provide a wide range of linear tunability for the filters [8]. Moreover, since the X-terminal resistance directly depends on the bias current of the CCCII (in the case of BJT structures), their values are sensitive to the temperature. Although the electronically tunable CM filter in [9] seems to be the most attractive one among the given circuits since it employs only two multi-output second-generation current controlled conveyors (MO-CCCIIs) and two capacitors but it requires two identical input currents which means an additional active element is required. Two of the proposed filters in [10] involve three inverting second generation

current conveyors (ICCIIs) and employ four grounded resistors and two grounded capacitors. The two filter circuits have independent control on Q and on the center frequency gain by varying a single grounded resistor but with only one output filter response and without tunability property. Recently, based on three dual-output current-controlled current differencing buffered amplifiers (DO-CCCDBAs) and two grounded capacitors a CM universal biquad filter with electronically tunable property via the input bias currents of the CCCDBAs has been presented in [1] performing only the three functions; LP, HP and BP. More recently, a filter with two-inputs and two-outputs based on ICCIIs with electronically tunable property has been proposed in [11]. However, the filter can neither produce all the three filter responses simultaneously nor produce bandstop (BS) and allpass (AP) responses.

It is worth noting that circuits employing only grounded passive elements have some advantages in integrated circuit realization. Also, a circuit employing minimum number of active and passive elements is attractive from the very large scale integration (VLSI) point of view.

This paper presents a multifunction biquad filter that is free from the drawbacks mentioned above. It has one input and three high-impedance outputs providing LP, BP and HP responses simultaneously. In addition, the notch (bandstop) and AP functions can be realized by connecting proper output currents without using additional active elements. It uses minimum number of capacitors (two capacitors), two MOS resistors which act as electronic resistors and three multi-output ICCIIs. The simulation results of the proposed filter configuration are given using SPICE program to verify the theoretical analysis.

## THE PROPOSED CIRCUIT

The ICCII is an active element with terminals namely Y, X and Z. The terminal voltage-current relationships of an ICCII can be expressed as:

$$I_Y = 0 \qquad\qquad .(1a)$$

$$V_X = -V_Y \qquad\qquad .(1b)$$

$$I_Z = \pm I_X \qquad\qquad .(1c)$$

The voltage at terminal X is the inversion of the voltage at terminal Y. The current at terminal Z follows the current at terminal X in magnitude. The plus and minus signs in (1c) indicate the plus and minus type of ICCII ($I_{Z+}=I_X$ or $I_{Z-}=-I_X$), respectively. The proposed CM single-input multi-output (SIMO) filter using three multi-output ICCIIs is illustrated in Figure (1). The second active element is the ICCII with three output currents which is called triple-output ICCII or TO-ICCII while the other two ones are ICCIIs, each with two output currents, which is called double-output ICCII or DO-ICCII. The filter circuit employs two grounded capacitors with two MOS resistors and realizes LP, BP and HP responses. It should be noted that the proposed filter has low

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input impedance due to the negative feedback loops and the output current signals are taken from high output impedance nodes. Moreover, since the voltage at terminal X is the inverse of the voltage at terminal Y of the ICCII a MOS resistor that behaves almost linearly can be achieved [13] as long as the MOS transistor is working in the triode region. Here its resistance value is given as:

$$R = \frac{1}{K_n (V_C - V_{th})} \qquad \ldots(2)$$

Where, $V_{th}$ is the threshold voltage and $K_n = \mu_n C_{ox}(W/L)$ is the transconductance parameter of the MOS transistor. Here $\mu_n$ is the surface mobility, $C_{ox}$ is the gate capacitance per unit area and (W/L) is the channel width/channel length of the transistor. In addition, $V_C$ is the control voltage applied to the gate of the transistor. This makes the proposed filter electronically tunable by adjusting the gate voltage of the MOS transistors. It is clear that this resistance is sufficiently linear for large signals, unlike the tunable X-terminal resistance of the CCCII, which is linear only for small signal amplitudes [7].

The corresponding transfer functions of the proposed single-input multi-output (SIMO) filter are given below.

$$\frac{I_{BP}}{I_{in}} = -\frac{\dfrac{2}{R_1 C_2} s}{s^2 + \dfrac{2}{R_1 C_2} s + \dfrac{4}{R_1 R_2 C_1 C_2}} \qquad \ldots (3a)$$

$$\frac{I_{LP}}{I_{in}} = \frac{\dfrac{4}{R_1 R_2 C_1 C_2}}{s^2 + \dfrac{2}{R_1 C_2} s + \dfrac{4}{R_1 R_2 C_1 C_2}} \qquad \ldots (3b)$$

$$\frac{I_{HP}}{I_{in}} = \frac{s^2}{s^2 + \dfrac{2}{R_1 C_2} s + \dfrac{4}{R_1 R_2 C_1 C_2}} \qquad \ldots (3c)$$

Eq.(3a), (3b) and (3c) represent the CM filter functions for BP, LP and HP responses, respectively. The natural frequency $\omega_o$ and the quality factor Q for the filter are given by:

$$w_o = \sqrt{\frac{4}{R_1 R_2 C_1 C_2}}, \quad Q = \sqrt{\frac{R_1 C_2}{R_2 C_1}} \qquad \ldots (4)$$

It is clear from (4) that $\omega_o$ and Q can be electronically tuned by adjusting the bias

voltage of MOS transistors (changing $R_1$ and $R_2$). In addition, it can be seen that the parameters $\omega_o$ and Q are orthogonally controllable by adjusting the ratio $R_1$ to $R_2$, $C_2$ to $C_1$ or $R_1 C_2$ to $R_2 C_1$.

In addition, a BS and AP responses can be obtained by interconnection of the relevant output currents as $I_{BS}=I_{LP}+I_{HP}$ and $I_{AP}=I_{LP}+I_{BP}+I_{HP}$, respectively, without using additional active elements.

Sensitivity analysis of the filter parameters shows that

$$S_{R_1}^{w_o} = S_{R_2}^{w_o} = S_{C_1}^{w_o} = S_{C_2}^{w_o} = S_{R_2}^{Q} = S_{C_1}^{Q} = -S_{R_1}^{Q} = -S_{C_2}^{Q} = -\frac{1}{2} \quad \dots (5)$$

which all are low.

## SIMULATION RESULTS

In order to confirm the theoretical validity of the proposed filter configuration given in Figure (1) it is simulated with SPICE simulation program. To implement the dual-output ICCIIs (DO-ICCIIs) the CMOS structure given in Figure (2) is used [10]. For additional Z- terminal (in case of tipple-output ICCII (TO-ICCII)) only two additional transistors (one PMOS and one NMOS) are simply connected to M14 and M17, respectively, as the two transistors M15 and M18 are connected. The aspect ratios of the MOS transistors are given in Table (1). The device model parameters from TSMC 0.35 μm CMOS process model parameters, given in Table (2), are used for the SPICE simulations and the supply voltages of $V_{DD}=-V_{SS}=1.5$ V and $V_{BB}=-0.9$ V are selected.

Simulated magnitude responses of the proposed filter circuit are given in Figure (3). For this purpose, equal equivalent resistances of 2.9 kΩ are taken and the capacitance values of $C_1$ and $C_2$ are taken as $C_1=2C_2=30$ pF for a natural frequency of $f_o \approx 2.58$ MHz and a quality factor of Q=0.707. The W/L ratio for the equal MOS resistors is chosen as 4.2/0.7. The results for the large-signal transient response of the BP response (as an example) is shown in Figure (4), where the input current is a sinusoidal signal of 180 μA (peak to peak) with a 2.58 MHz frequency. The total harmonic distortion is found to be 0.77%. Maximum power consumption is about 5.2 mW.

The magnitude and phase responses for AP output current ($I_{HP}+I_{LP}+I_{BP}$) at 2.58 MHz is illustrated in Figure (5).

**Table (1) transistor aspect ratios of the DO-ICCII circuit Shown in Figure (2).**

| Transistor | W (μm) | L (μm) |
|---|---|---|
| M1-M4 | 1.4 | 0.7 |
| M5-M6 | 5.6 | 0.7 |
| M7, M8, M13, M14, M15 | 14 | 0.7 |
| M9-M10 | 20.3 | 0.7 |
| M11, M12, M16, M17, M18 | 58.1 | 0.7 |

**Table (2) the 0.35 μm TSMC CMOS Model Parameters.**

```
.MODEL CMOSN NMOS ( LEVEL=3
+TOX=7.9E-9 NSUB=1E17 GAMMA=0.5827871
+PHI=0.7 VTO=0.5445549 DELTA=0
+UO=436.256147 ETA=0 THETA=0.1749684
+KP=2.055786E-4 VMAX=8.309444E4 KAPPA=0.2574081
+RSH=0.0559398 NFS=1E12 TPG=1
+XJ=3E-7 LD=3.162278E-11 WD=7.046724E-8
+CGDO=2.82E-10 CGSO=2.82E-10 CGBO=1E-10
+CJ=1E-3 PB=0.9758533 MJ=0.3448504
+CJSW=3.777852E-10 MJSW=0.3508721 )

.MODEL CMOSP PMOS ( LEVEL=3
+ TOX=7.9E-9 NSUB=1E17 GAMMA=0.4083894
+ PHI=0.7 VTO=-0.7140674 DELTA= 0
+ UO=212.2319801 ETA=9.999762E-4 THETA=0.2020774
+ KP=6.733755E-5 VMAX=1.181551E5 KAPPA=1.5
+ RSH=30.0712458 NFS=1E12 TPG=-1
+ XJ=2E-7 LD=5.000001E-13 WD=1.249872E-7
+ CGDO=3.09E-10 CGSO=3.09E-10 CGBO=1E-10
+ CJ=1.419508E-3 PB=0.8152753 MJ=0.5
+ CJSW=4.813504E-10 MJSW=0.5 )
```
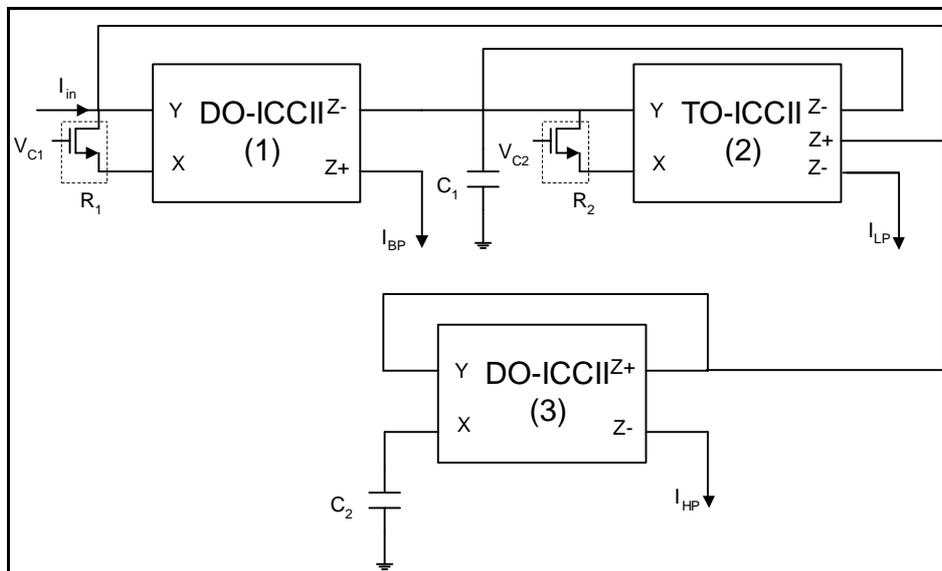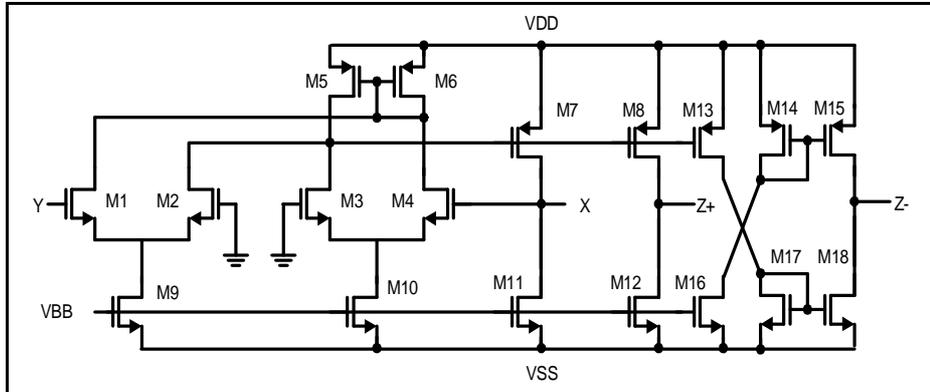


**Figure (1) the proposed SIMO CM filter.**

**Figure (2) the CMOS realization of DO-ICCII used for the simulations Figure (3) adopted from [10].**

To show the electronically tunability of the proposed filter, different values of $V_{C1}$ and $V_{C2}$ as 0.8 V, 0.9 V and 1 V are selected to obtain resonance frequencies of 0.9 MHz, 2.31 MHz, and 4.1 MHz, respectively. The results are shown for the BP response, as an example, in Figure (6).
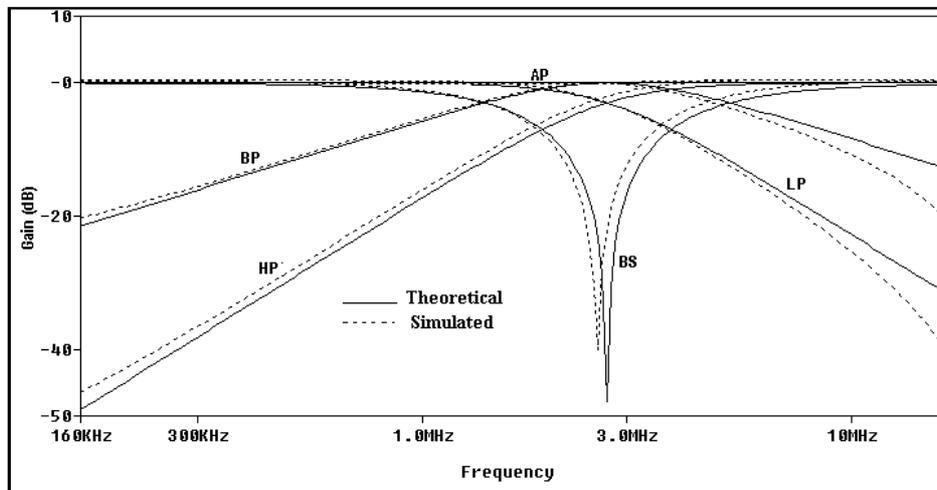


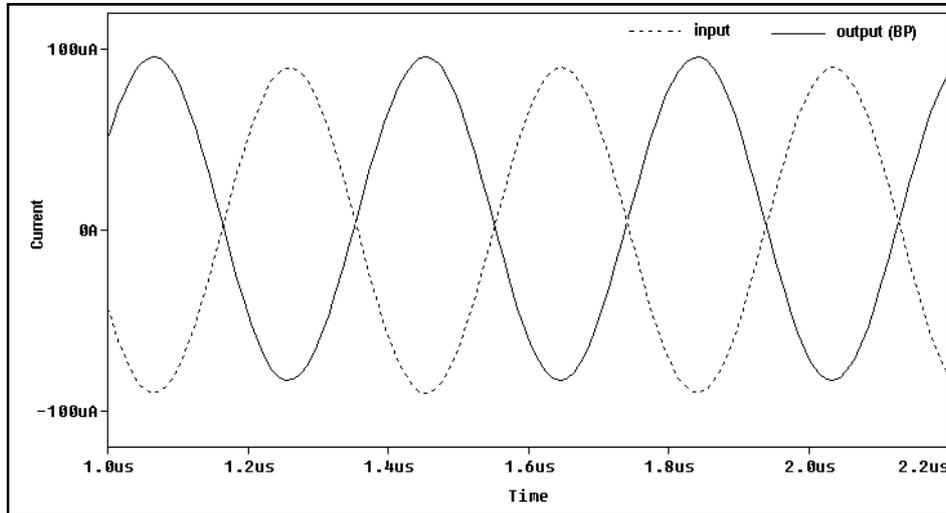**Figure (3) magnitude responses of the proposed filter for BP, LP, HP, BS and AP responses.**

**Figure (4)    the input and output current waveforms of the BP response for 180 µA (peak-to-peak) sinusoidal input current at 2.58 MHz.**
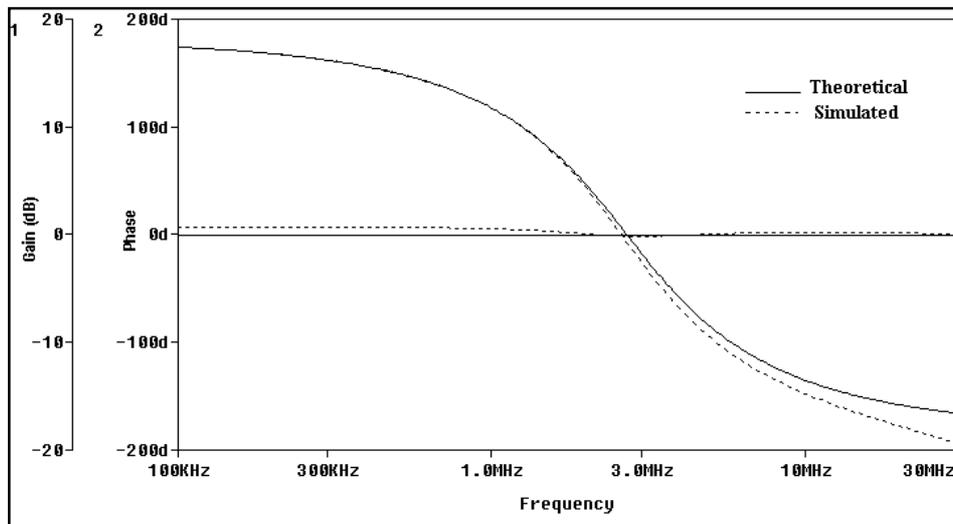


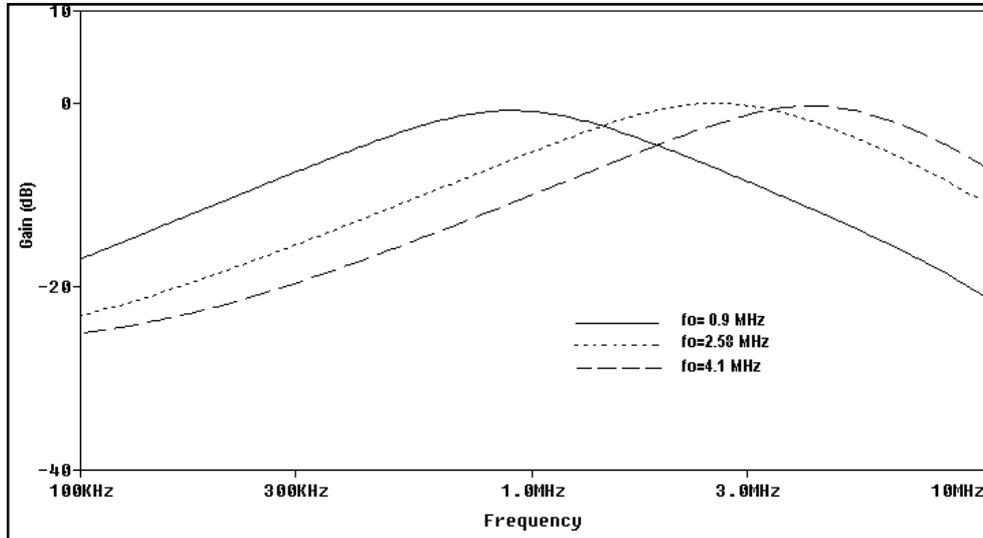**Figure (5) the magnitude and phase responses for AP response at 2.58 MHz.**

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**Figure (6) magnitude of the BP response for different control voltages.**

## CONCLUSIONS

A CM SIMO multifunction filter using only three inverting current conveyors is proposed in this work. The validity of the proposed filter has been demonstrated through SPICE simulations. It can be observed from the simulation results that they agree well with the theoretical ones. However, the differences between ideal (theoretical) and simulated responses mainly stem from the parasitic effects and non-ideal current and voltage gains of the multi-output ICCIIs

The proposed filter has been found to have the following advantages:

(i) Low frequency and Q-factor sensitivities

(ii) Employing only grounded capacitors so it is easy to realize the proposed filter in IC process

(iii) It is free from the critical active and passive component matching conditions and/or cancellation constraints

(iv) No need to employ inverting-type current input signal or double input current signal to realize all three basic filter functions.

(v) The high impedance outputs enable easy cascadability without the need of any supplementary buffer circuits.

(vi) Capability of electronically adjusting of the parameters $\omega_o$ and Q, through adjusting the bias voltage of MOS resistors

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