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مرشح الكتروني جديد مختلط نموذج بيكواد قابل للانضباط

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الخلاصة

تقدم هذه الورقة مرشح مختلط انضباطي إلكتروني عالمي جديد Biquad الذي يتكون أساسا من ناقل تيار وحيد أدخل حديثا لتعديل الناقل الحالي العابر لتصرف مكبر للصوت (MCCTA) كعنصر نشط واثنين من المكثفات، واثنين من المقاومات كعناصر سلبية. طوبولوجيا المرشح يمكن تحقيق تمرير مرشح منخفض (LP)، وتمرير الفرقة (BP)، ومرشح عالي (HP)، ومرشح رافض (BR) وسلوك كل المرشحات يعبرون عن ردود التصفية في أربعة أنماط مختلفة وهي نمط التيار (CM)، ونمط الجهد (VM)، ونمط عبر المقاومة (TIM)، ونمط القبول (TAM)، من خلال تطبيق شروط واختيار المدخلات والمخرجات المناسبة. في حين تعمل، الدائرة لا تحتاج إلى أي نوع مقلوب و/ أو نوع تحجيم إشارة المدخلات الجهد الحالي / (ق) لأي من تحقيق استجابة التصفية. ومن المشجع أيضا للحفاظ على ميزة من قابلية انضباط إلكتروني لعامل الجودة، بالإضافة الى عرض الحزمة مستقلة وكذلك التغير في تردد القطب، إلا من خلال تيار واحد من العنصر النشط. يتم محاكاة المرشح المقترح من خلال برنامج PSPICE باستخدام تكنولوجيا CMOS القياسية ويقدم الحساسيات التدريجية الايجابية والسلبية.

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A new electronically tunable universal mixed-mode biquad filter

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ABSTRACT

This paper introduces a new electronically tunable universal mixed-mode biquad filter topology, which mainly consists of single newly introduced modified current conveyor trans-conductance amplifier (MCCTA) as active element and two capacitors, two resistors as passive elements. The filter topology can realize low pass (LP), band pass (BP), high pass (HP), band reject (BR) and all pass (AP) filtering responses in four different possible modes of operation namely, current-mode (CM), voltage-mode (VM), trans-impedance-mode (TIM), and trans-admittance-mode (TAM), through applying appropriate conditions and selection of inputs and outputs. While operating, the circuit does not need any inverted type and/or scaled type current/voltage input signal(s) for any of the filtering response realization. It is also encouraging to sustain the feature of interactive electronic tunability of quality factor as well as band-width independent of pole frequency variation, only through single biasing current of the active element. The proposed filter is simulated through PSPICE software using standard CMOS technology and offers low incremental active and passive sensitivities.

Keywords: Analog signal processing; biquad; filter; mixed-mode; universal.

INTRODUCTION

State of the art electronics and communication equipments demand high performance analog signal processing functions, among them continuous time analog filters are one of the most demanded circuits. The biquad filter circuits realizing different filtering functions in current-mode (Soliman, 1991; Biolek *et al*., 2003 and Keskin *et al.,* 2006), voltage-mode (Maheshwari, 2008; Chang *et al*., 1999 and Horng *et al.,* 1996), trans-Impedance-mode (Soliman, 1996) and trans-admittance-mode (Beg *et al.,* 2013 and Toker *et al.,* 2001) from same configuration, are termed as mixed-mode filters. In recent past, mixed-mode filter circuits have been extensively studied and researched in open literature with renewed interest and hence, several mixed-mode filter circuits using different current-mode active elements such as CCII (Abuelma'atti *et al.*, 2004 and Pandey *et al., 2*006), DDCCII (Liao *et al*., 2011 and Lee, 2011), CFOA (Singh *et al.,* 2005), CCCII (Abuelma'atti *et al*., 2003 and Zhijun, 2009), OTAs (Abuelma'atti et al., 2005; Lee, 2009 and Chen *et al.,* 2009), CCCCTA (Maheshwari *et al.,* 2011 and Singh *et al.,* 2011) and FDCCII (Lee *et al*., 2009) etc. are reported in the literature. Among them mixed-mode filters circuits in (Pandey *et al.,* 2006; Liao et al., 2011; Lee, 2011; Singh *et al.,* 2005; Abuelma'atti *et al*., 2003; Maheshwari *et al.,* 2011 and Singh *et al.,* 2011) employ three (Pandey *et al.,* 2006; Liao *et al*., 2011; Lee, 2011; Maheshwari *et al.,* 2011 and Singh *et al.,* 2011) or four (Singh *et al.,* 2005 and Abuelma'atti *et al*., 2003) active elements, whereas other circuits (Abuelma'atti *et al.,* 2004; Zhijun, 2009; Abuelma'atti *et al*., 2005; Lee, 2009 and Chen *et al.,* 2009) use five (Abuelma'atti *et al.,* 2004; Zhijun, 2009; Lee, 2009 & Chen *et al.,* 2009), six (Abuelma'atti *et al.,* 2004) or eight (Abuelma'atti *et al*., 2005) active elements. In addition to this, these filter circuits also contains two (Abuelma'atti *et al*., 2003; Zhijun, 2009; Abuelma'atti *et al*., 2005; Lee, 2009; Chen *et al.,* 2009; Maheshwari *et al.,* 2011 and Singh *et al.,* 2011), five (Lee, 2011), six (Pandey *et al.,* 2006 and Liao *et al.,* 2011), nine (Abuelma'atti *et al.,* 2004), ten (Abuelma'atti *et al.,* 2004), or eleven (Singh *et al.,* 2005) passive elements. Moreover, except (Abuelma'atti, 2003; Zhijun, 2009; Maheshwari *et al.,* 2011 and Singh *et al.,* 2011), each circuits in (Abuelma'atti *et al.,* 2004; Pandey *et al.,* 2006; Liao *et al.,* 2011; Lee, 2011; Singh *et al.,* 2005; Abuelma'atti *et al*., 2005; Lee, 2009 and Chen *et al.,* 2009) realizes all the five standard filter functions in each possible operating mode. However, these circuits employ too many active and passive elements in filter realization. Beside it, few of the circuits (Abuelma'atti *et al.,* 2004; Pandey *et al.,* 2006; Liao *et al*., 2011; Lee, 2011 and Singh *et al.,* 2005), don't offer the current tunability feature of filter characteristic parameters too. As far as the topic of this paper is concerned, the mixed-mode filter circuits using single active element are of great interest, because circuits employing minimum (single) active components are more beneficial in terms of power dissipation and manufacturing cost point of view and also satisfy the supply related specifications of portable battery operated electronic gadgets. Only one mixed-mode filter employing single FDCCII as active element and two capacitors, three resistors as five passive elements is found in the available literature (Lee *et al.,* 2009). It can realize all the standard filtering functions (LP, BP, HP, RN, AP) in CM, VM and TIM modes, but can realize only two filtering functions (BP and HP) in TAM mode. It still suffers from the lack of electronic adjustment properties of filter characteristic parameters too.

In this paper, a new electronically tunable universal mixed-mode biquad filter based on single MCCTA is presented. It also employs two capacitors and two resistors. With current signal(s) as input(s), the proposed filter can realize all the standard filtering functions in both CM and TIM modes. Similarly, when voltage signal(s) are applied as input(s), the proposed filter can realize all the standard filtering functions in both VM and TAM modes. The incremental active and passive sensitivity offered by the proposed filter are low. The proposed circuit is analyzed for non-ideal MCCTA and its performance is evaluated through P-SPICE using 0.25μm TSMC CMOS parameters (Prommee *et al.,* 2009) and various simulated responses along with thorough discussion are demonstrated which show good agreement with the theory.

BASICS OF MCCTA

The conventional CCTA (Herencsar *et al.,* 2009 and Singh *et al.,* 2013), is relatively a new active element, receives errand of circuit designers for its suitability and versatility in the realization of a class of analog signal processing circuits, especially analog frequency filters. MCCTA is the modified version of conventional CCTA and it offers the advantage of a supplementary electronic tunability opportunity over conventional CCTA. The terminals current-voltage relationships for MCCTA can be described as;

$$\begin{bmatrix} I_Y \\ V_X \\ I_{Z1} \\ I_{Z2} \\ I_{Z3} \\ I_{-O1} \\ I_{-O2} \end{bmatrix} = \begin{bmatrix} 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 & 0 \\ 1 & 0 & 0 & 0 & 0 & 0 & 0 \\ 1 & 0 & 0 & 0 & 0 & 0 & 0 \\ 1 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & -g_{m1} & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & -g_{m2} & 0 & 0 & 0 \end{bmatrix} \begin{bmatrix} I_X \\ V_Y \\ V_{Z1} \\ V_{Z2} \\ V_{Z3} \\ V_{-O1} \\ V_{-O2} \end{bmatrix} \tag{1}$$

Where, g_{m1} and g_{m2} are trans-conductance parameters of MCCTA, whose values depend on biasing currents I_{S1} and I_{S2}, respectively. The electrical symbol of MCCTA is illustrated in Figure 1. The CMOS implementation of employed MCCTA is also shown in Figure 2. For CMOS based MCCTA (Tomar *et al.,* 2013), the expressions of g_{m1} and g_{m2} can be given as

$$g_{m1} = \sqrt{\beta_n I_{S1}} \text{ and } g_{m2} = \sqrt{\beta_n I_{S2}} \tag{2}$$

$$\text{Where } \beta_n = \mu_n C_{OX} \frac{W}{L} \tag{3}$$

Where, μ_n, C_{OX} and W/L are the electron mobility, gate oxide capacitance per unit area and aspect ratio of NMOS transistors M_8-M_9, M_{12}-M_{13}, respectively. I_{S1} and I_{S2} are the biasing currents of MCCTA.

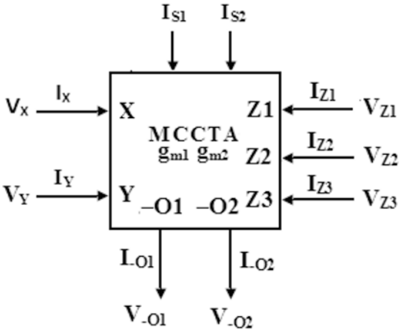


Fig. 1. MCCTA Symbol

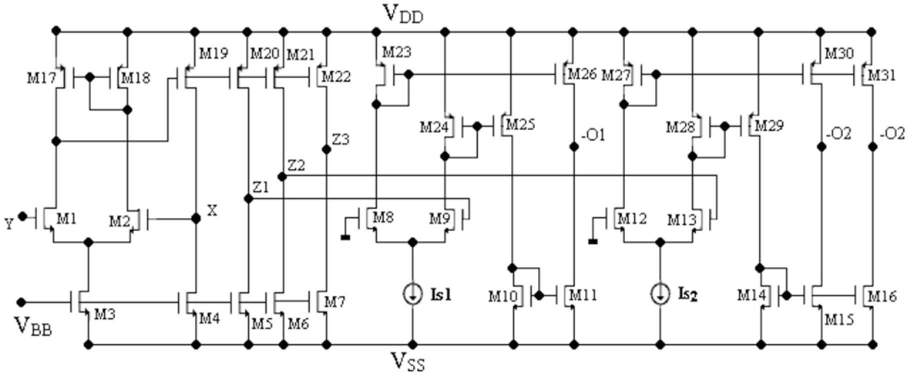


Fig. 2. CMOS implementation of MCCTA

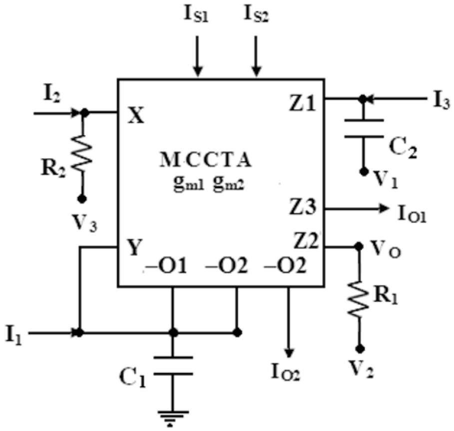


Fig. 3. Proposed mixed-mode universal biquad filter

PROPOSED MIXED-MODE FILTER CIRCUIT

The proposed mixed-mode biquad filter using single MCCTA is shown in Figure 3 which also employs two capacitors and two resistors as passive elements. If we put the input voltage signals (V_1=V_2=V_3=0) to zero and only input current signals (I_1, I_2 and I_3) are applied to the circuit, a usual analysis of the circuit topology in Figure 3 yields the following output current I_{O1} and output voltage V_O, as specified in Equations (4) and (5).

$$I_{O1} = -\frac{I_2 s^2 C_1 C_2 R_2 - I_1 s C_2 + I_3 g_{m1}}{s^2 C_1 C_2 R_2 + s C_2 R_1 g_{m2} + g_{m1}} \tag{4}$$

$$V_O = -R_1 \frac{I_2 s^2 C_1 C_2 R_2 - I_1 s C_2 + I_3 g_{m1}}{s^2 C_1 C_2 R_2 + s C_2 R_1 g_{m2} + g_{m1}} \tag{5}$$

From Equations (4) and (5), it is clear that various filtering responses in both CM as well as TIM modes can be obtained at I_{O1} and V_O, respectively through appropriate selection of input current signals (I_1, I_2 and I_3).

(i) Inverted HP response in current and trans-impedance-mode, with $I_2=I_{in}$ and $I_1=I_3=0$.

(ii) Inverted LP in current and trans-impedance-mode, with $I_3=I_{in}$ and $I_1= I_2=0$.

(iii) Non-inverted BP response in current and trans-impedance-mode, with $I_1=I_{in}$ and $I_2=I_3=0$.

(iv) Inverted BR response in current and trans-impedance-mode, with $I_2=I_3=I_{in},$ *and* $I_1=0$.

(v) Inverted AP response in current and trans-impedance-mode, with $I_1=I_2=I_3=I_{in}$, and $g_{m2}R_1=1$.

Further, if the input current signals are detached and only input voltage signals (V_1, V_2 and V_3) are applied to the circuit, the routine analysis of Figure 3 provides the following output current (I_{O2}) and voltage (V_O) expressions,

$$I_{O2} = -g_{m2}\left[\frac{V_2(s^2 C_1 C_2 R_2 + s g_{m2} R_1 C_2 + g_{m1}) - V_1 s g_{m1} R_1 C_2 - V_2 s g_{m2} R_1 C_2 - V_3 s^2 C_1 C_2 R_1}{s^2 C_1 C_2 R_2 + s g_{m2} R_1 C_2 + g_{m1}}\right] \tag{6}$$

$$V_O = \left[\frac{V_2(s^2 C_1 C_2 R_2 + s g_{m2} R_1 C_2 + g_{m1}) - V_1 s g_{m1} R_1 C_2 - V_2 s g_{m2} R_1 C_2 - V_3 s^2 C_1 C_2 R_1}{s^2 C_1 C_2 R_2 + s g_{m2} R_1 C_2 + g_{m1}}\right] \tag{7}$$

It is accomplished from Equations (6) and (7) that various TAM and VM mode filtering responses can be obtained at I_{O2} and V_0, respectively, through appropriate selection of input voltages.

(i) Inverted HP in voltage-mode and non-inverted HP in trans-admittance-mode with $V_1=V_2=0$ and $V_3=V_{in}$.

(ii) Inverted BP in voltage-mode and non-inverted BP in trans-admittance-mode with $V_2=V_3=0$ and $V_1=V_{in}$.

(iii) Non-inverted LP in voltage-mode and inverted LP in trans-admittance-mode with $V_2=V_3=V_{in}$, $V_1=0$ and $R_1=R_2$

(iv) Non-inverted BR in voltage-mode and inverted BR in trans-admittance-mode with $V_1=V_3=0$ and $V_2=V_{in}$.

(v) Non-inverted AP in voltage-mode and inverted AP in trans-admittance-mode with $V_1=V_2=V_{in}$, $V_3=0$ and $g_{m1}= g_{m2}$.

Thus, the proposed circuit in Figure 3 is competent of realizing all the five standard filtering functions in CM, TIM, VM, and TAM modes from the same configuration without requiring any inverted and/or double current/voltage input signal(s). However, few filter realization requires matching condition, but this can be reasonable as only single active element is used to design the proposed circuit. The characteristic parameters of the filter like pole frequency (ω_o), the quality factor (Q) and bandwidth (BW) can be derived and expressed as;

$$\omega_o = \left(\frac{g_{m1}}{C_1C_2R_2}\right)^{\frac{1}{2}} = \left(\frac{1}{C_1C_2R_2}\sqrt{\beta_n I_{S1}}\right)^{\frac{1}{2}} \tag{8}$$

$$Q = \frac{1}{R_1 g_{m2}}\left(\frac{C_1R_2g_{m1}}{C_2}\right)^{\frac{1}{2}} = \frac{1}{R_1}\left(\frac{C_1}{C_2}\frac{R_2}{I_{S2}}\sqrt{\frac{I_{S1}}{\beta_n}}\right)^{\frac{1}{2}} \tag{9}$$

$$\text{and } BW = \frac{\omega_o}{Q} = \frac{1}{C_1}\frac{R_1}{R_2}\left(\beta_n I_{S2}\right)^{\frac{1}{2}} \tag{10}$$

It is apparent from Equations (8) and (9) that the Q can be controlled independently through single biasing current I_{S2} without influencing ω_o. In addition, from Equations (8) and (10) it is evident that ω_o can be also tuned independent of BW by varying biasing current I_{S1}.

To identify the effects of involved non idealities, the non ideal MCCTA's terminal relationships can be articulated with the help of following set of equations;

$$V_X = \beta V_Y, I_{Z1,Z2,Z3} = \alpha I_X, I_{-O1} = -\gamma_1 g_{m1} V_{Z1}, I_{-O2} = -\gamma_2 g_{m2} V_{Z2} \tag{11}$$

Where β, α, γ_1 and γ_2 are transferred tracking error from Y to X terminal., X to Z1 (or Z2, Z3) terminals, Z1 to –O1 and Z2 to –O2 terminal respectively. Ideally, these tracking errors should be unity and frequency independent. In a practical device, these are found to be slightly less than unity. On re-analyzing the proposed filter in Figure 3 with the aforesaid non-idealities, the denominator of expression in each operating mode turns out to be;

$$D(s) = s^2 C_1 C_2 R_2 + s\alpha\beta\gamma_2 C_2 R_1 g_{m2} + \alpha\beta\gamma_1 g_{m1} \tag{12}$$

In this case, the ω_o and Q are altered to

$$\omega_o = \left(\frac{\alpha\beta\gamma_1 g_{m1}}{C_1 C_2 R_2} \right)^{\frac{1}{2}}, \; Q = \frac{1}{\gamma_2 R_1 g_{m2}} \left(\frac{\gamma_1 C_1 g_{m1} R_2}{\alpha\beta C_2} \right)^{\frac{1}{2}} \tag{13}$$

From Equation (13), the all active and passive sensitivities are analyzed and can be found as

$$S^{\omega_o}_{C_1, C_2, R_2} = -\frac{1}{2}, \; S^{\omega_o}_{\alpha, \beta, \gamma_1, g_{m1}} = \frac{1}{2}, \; S^{\omega_o}_{\gamma_2, R_1} = 0 \tag{14}$$

$$S^{Q}_{C_2, \alpha, \beta} = -\frac{1}{2}, \; S^{Q}_{C_1, \gamma_1, R_2, g_{m1}} = \frac{1}{2}, \; S^{Q}_{\gamma_2, R_1, g_{m2}} = -1 \tag{15}$$

From the calculations of sensitivities done in Equations (14) – (15), it can be concluded that magnitude of the entire active and passive sensitivities are low as within ‘unity’.

PARASITIC STUDY

In this section, the parasitic impedance effect of the employed MCCTA on the performance of the proposed mixed-mode filter is to be considered. Equations (4)-(7) were derived using an ideal MCCTA. In practical applications implementing the practical MCCTA by using MOS transistors must be assumed with its various ports parasitic as represented in Figure 4. It is shown that the MCCTA has a low value parasitic series resistance (R_X) at port X, and high input impedance parasitic in the form of $R_Y \| C_Y$ at port Y. Also, the output ports Z_1, Z_2, and $-O_1$, $-O_2$ exhibit high output impedances parasitic in the form of $R_{Z1} \| C_{Z1}$, $R_{Z2} \| C_{Z2}$, $R_{O1} \| C_{O1}$, $R_{O2} \| C_{O2}$, respectively. Let us analyze the effect of parasitic of the circuit operated in current-mode and transimpedence-mode by applying the current inputs (I_1, I_2, I_3) and keeping $V_1=V_2=V_3=0$. The parasitic resistance R_x at port X is merged with R_2 which does not affect the performance of the filter in CM and TIM mode. It is further noted that the proposed circuit employs external capacitors C_1, C_2, and resistor R_1 connected at ports Y, Z_1, and Z_2, respectively. Hence to minimize the effect of parasitic impedance across different terminals, the following conditions must be satisfied:

$$\left|\frac{1}{\omega C_1}\right| << (R_Y // R_{O1} // R_{O2}), \quad \left|\frac{1}{\omega C_2}\right| << R_{Z1}, \quad \left|\frac{1}{\omega C_{Z1}}\right| >> (R_1 // R_{Z2}) \qquad (16)$$

Where, $(C_1 = C_2) >> C_{Z1}, C_{Z2}, C_Y, C_{O1}, C_{O2}$. It is apparent that the conditions in (16) are easily achievable in practice. Similarly, we can also analyze the effect of parasitic impedance of MCCTA on the performance of the proposed circuit in VM and TAM.

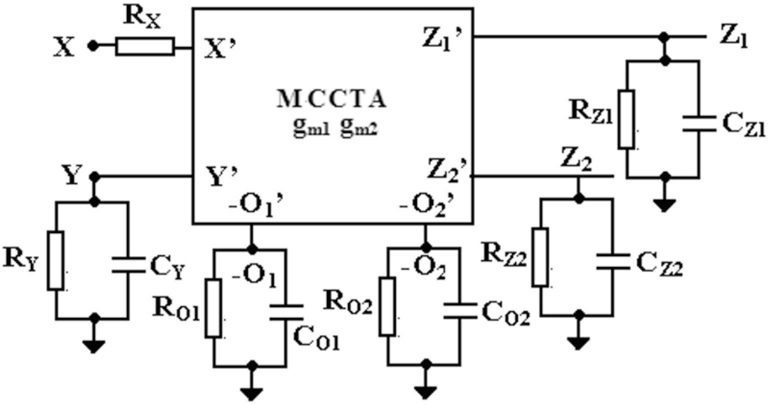


Fig. 4. Ports parasitic of practical MCCTA

SIMULATION RESULTS

The performance of the newly proposed single MCCTA based mixed-mode filter in Figure 3 was verified using PSPICE simulations. For simulation, the MCCTA was implemented using CMOS as shown in Figure 2, with dimensions (W/ L) of each MOS as given in Table 1. The 0.25μm (Prommee *et al.,* 2009) and 0.18μm (Chen, 2014) CMOS model parameters from TSMC were used to simulate the proposed circuit.

In design, the circuit components values to achieve $f_o = \omega_o/2\pi$ = 12.16 MHz at Q=1 were selected as $I_{S1} = I_{S2}$ = 100μA, $R_1 = R_2$ = 0.77KΩ, $C_1 = C_2$ = 17pF, $V_{DD} = -V_{SS}$ = 1.25V and V_{BB} = -0.57V. The simulated gain and phase responses of HP, LP, BP, BR, and AP in CM and TAM modes, for the proposed circuit are shown in Figure 5 and Figure 6, respectively. Similarly, the simulated gain responses of HP, LP, BP, BR, and AP in VM and TIM modes are shown in Figure 7 and Figure 8, respectively. The simulated pole frequency is obtained as 12.02 MHz, which is fairly closed to the designed value.

Next, the simulation was performed to demonstrate interactive electronic tuning aspects of Q independent to pole frequency through single biasing current I_{S2}. For this, the gain and phase responses of both voltage-mode HP and trans-impedance mode BP responses are obtained as shown in Figure 9 and Figure 10 for different values of biasing current I_{S2} by keeping I_{S1} as constant (I_{S1} = 100μA), which proves an interactive electronic tuning of Q without influencing pole frequency. Consequently, high Q filters can be realized by controlling biasing current I_{S2}. Figure11 shows the simulation results showing electronic tuning of pole frequency independent of BW which has been done by keeping I_{S2} as constant (I_{S2} = 100μA) and on varying I_{S1} between 30μA to 400μA. The pole frequency has been tuned between 7.08 MHz to 15.14 MHz, without affecting the bandwidth of filtering responses.

Further, to inspect the input dynamic range of the proposed mixed-mode circuit, time domain behavior of the circuit was simulated with a sinusoidal current input signal with peak to peak amplitude of 120μA and frequency 200 KHz. The simulated time domain results for both CM and TIM-mode LP responses is shown in Figure 12. Similarly, time domain behavior of HP responses in both VM and TAM-mode was also obtained by applying an input voltage with peak to peak amplitude of 200mV at signal frequency of 15 MHz and corresponding simulation results is illustrated in Figure13. The total harmonic distortion (THD) variations of current-mode BP response at 12.02 MHz is shown in Figure 14, which indicates that the THD figures are within the acceptable limit (3%) up to 70 μA amplitude of the current input signal, which shows a fairly moderate THD performance. To perceive the effects of capacitive deviations on the performance of proposed circuit, Monte-Carlo simulation of the proposed circuit with 5% Gaussian deviation in values of capacitors $C_1 = C_2 = 17$ pF has been performed simultaneously for hundred samples. The statistical results for voltage-mode BP response is shown in Figure 15, for the TSMC 0.25μm technology parameters the simulated mean, median and standard deviations were respectively, 13.1 MHz, 13.08 MHz and 275.34 KHz. Similar Monti-Carlo analysis using TSMC 0.18μm technology parameters was also performed. As a result, the mean, median and standard deviations were found 12.84 MHz, 12.81 MHz and 244.58 KHz respectively, which reveals that the proposed filter offers reasonable sensitivity figures for both 0.25μm and 0.18μm technology. Next, the input noise and voltage-mode HP output noise of the proposed mixed-mode circuit was investigated for both 0.18μm and 0.25μm technologies at different frequencies and corresponding simulation results are shown in Figure 16. From the results it was observed that output voltage noise for 0.18μm is reduced by 12.159 dB in comparison to the output voltage noise for 0.25μm technology. Thus the time domain analysis, Monte-Carlo and Noise spectral analysis for 0.18μm and 0.25μm technology simulation of the proposed mixed-mode circuit confirm its practical utility.

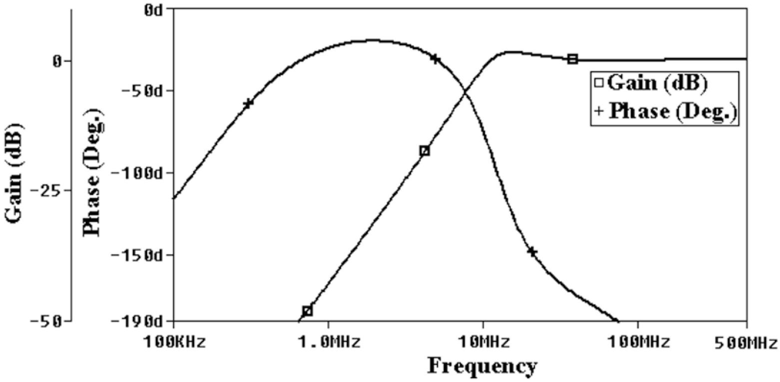


Fig. 5. (a)

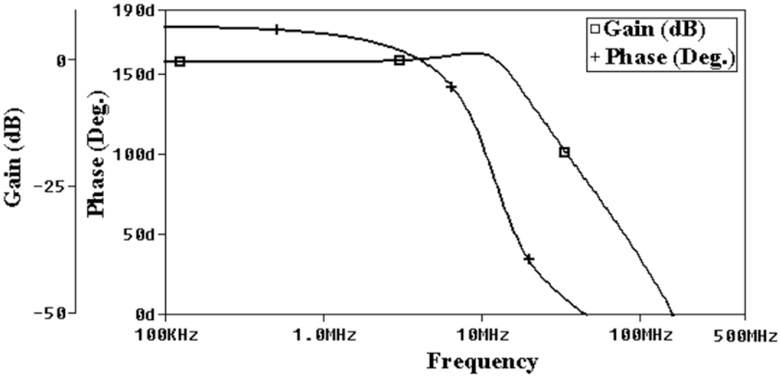


Fig. 5. (b)

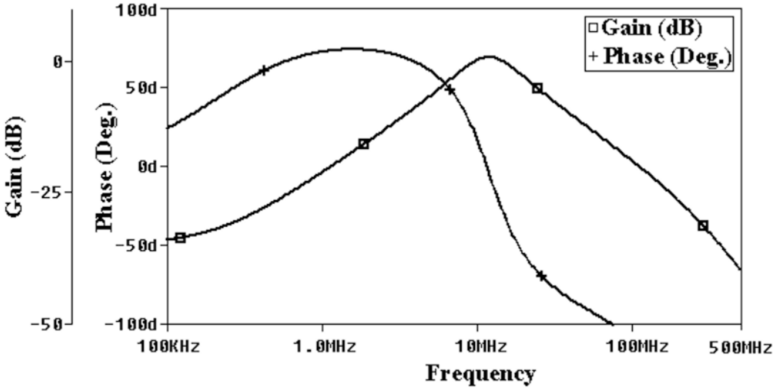


Fig. 5. (c)

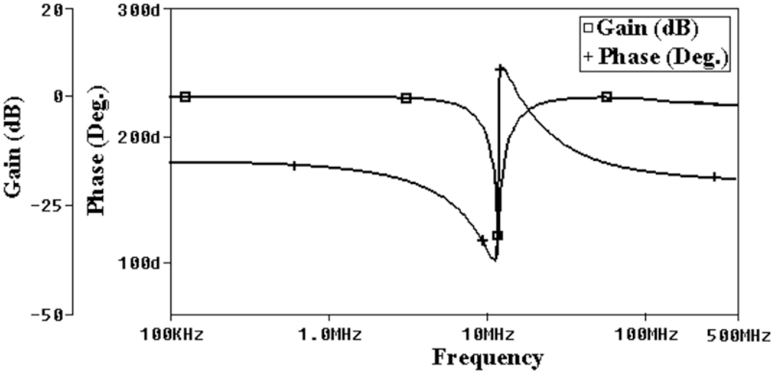


Fig. 5. (d)

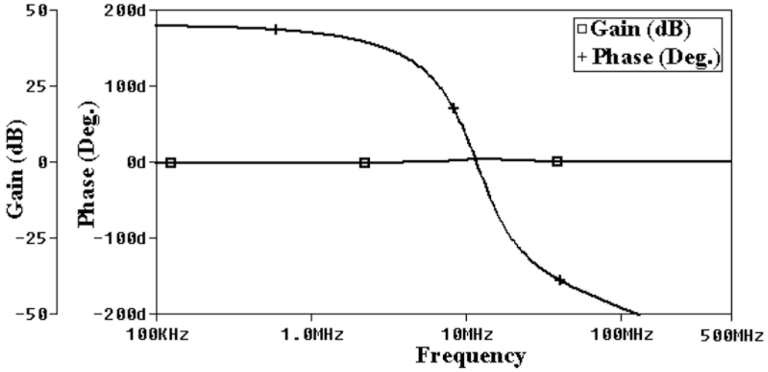


Fig. 5. (e)

Fig. 5. Current gain and phase responses of the proposed mixed-mode filter **(a)** HP, **(b)** LP, **(c)** BP, **(d)** BR, and **(e)** AP

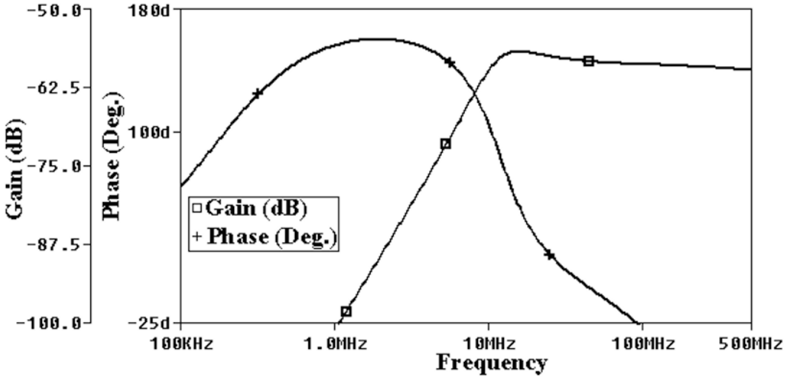


Fig. 6. (a)

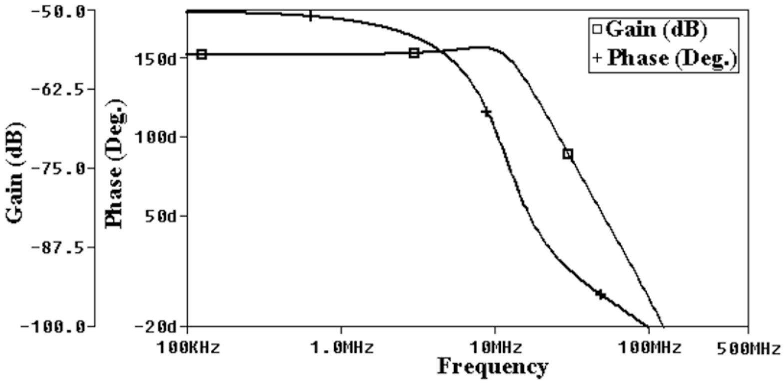


Fig. 6. (b)

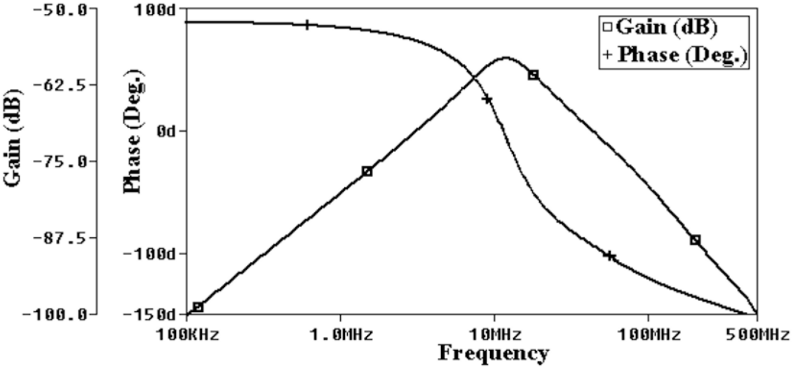


Fig. 6. (c)

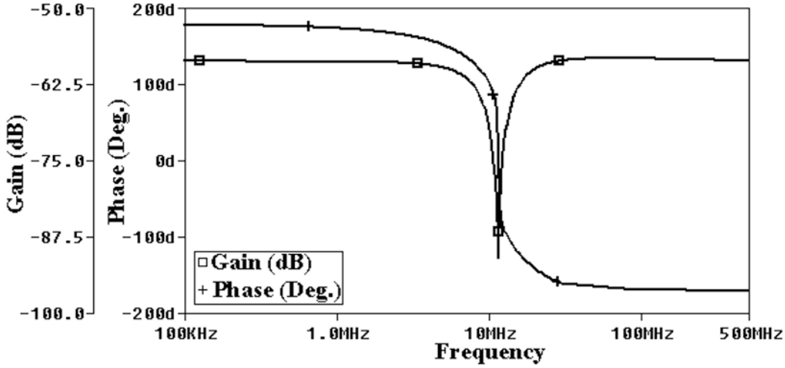


Fig. 6. (d)

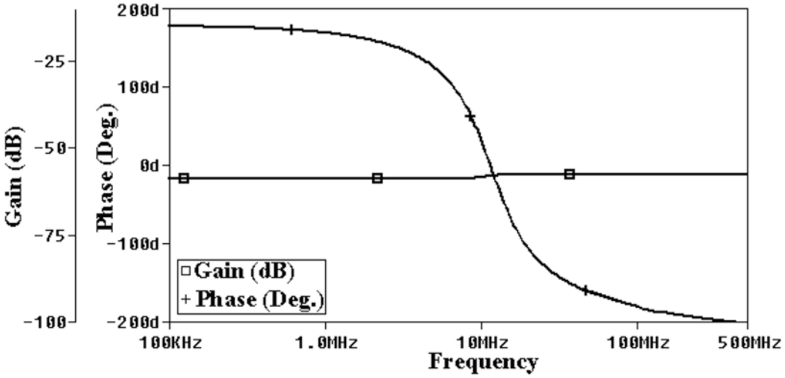


Fig. 6. (e)

Fig. 6. Trans-admittance gain and phase responses of the proposed mixed-mode filter **(a)** HP, **(b)** LP, **(c)** BP, **(d)** BR, and **(e)** AP

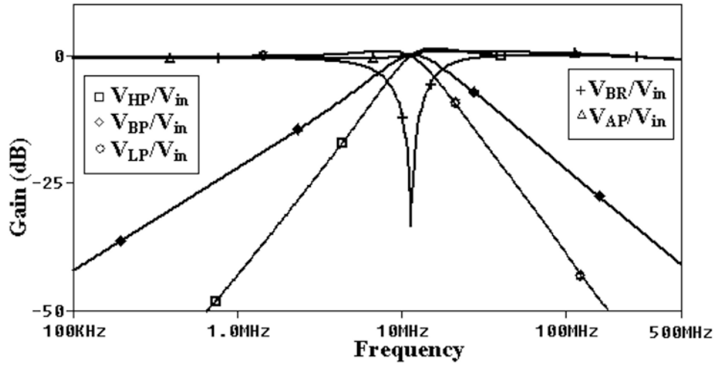


Fig. 7. Voltage gain of HP, BP, LP, BR and AP of the proposed mixed-mode filter

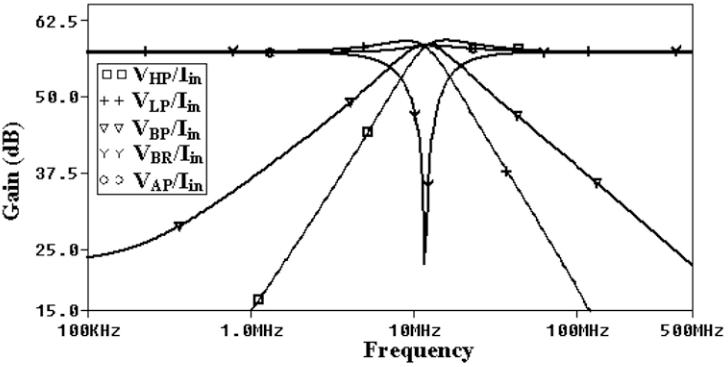


Fig. 8. Trans-impedance gain of HP, LP, BP, BR and AP of the proposed mixed-mode filter

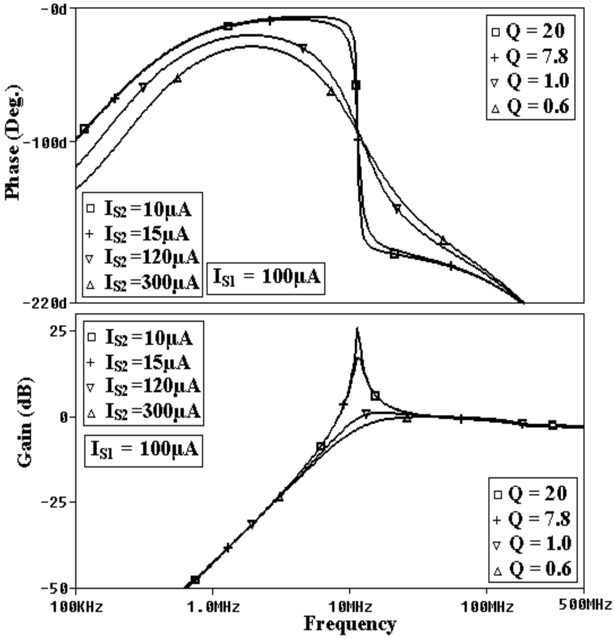


Fig. 9. HP Peaking versus Q in voltage-mode of the proposed filter for different values of I_{S2}

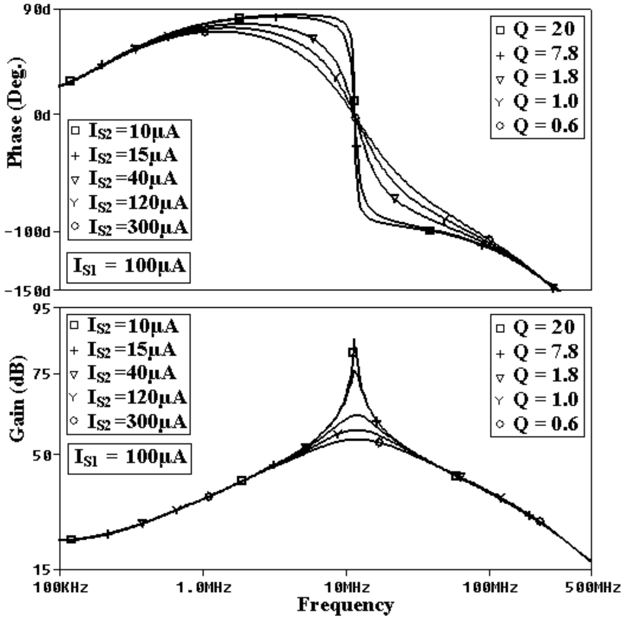


Fig. 10. BP responses in trans-impedance-mode of the proposed filter for different values of I_{S2}

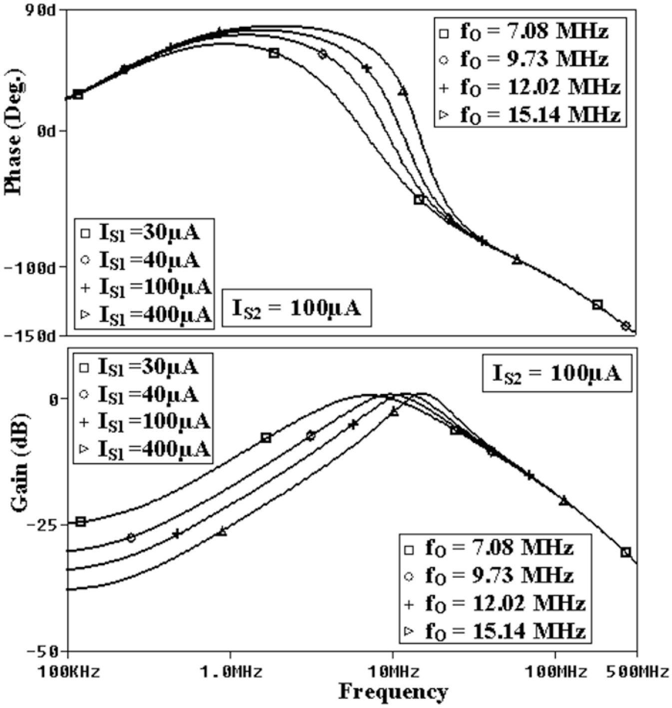


Fig. 11. Pole frequency variation of BP response in current-mode for different values of I_{S1}

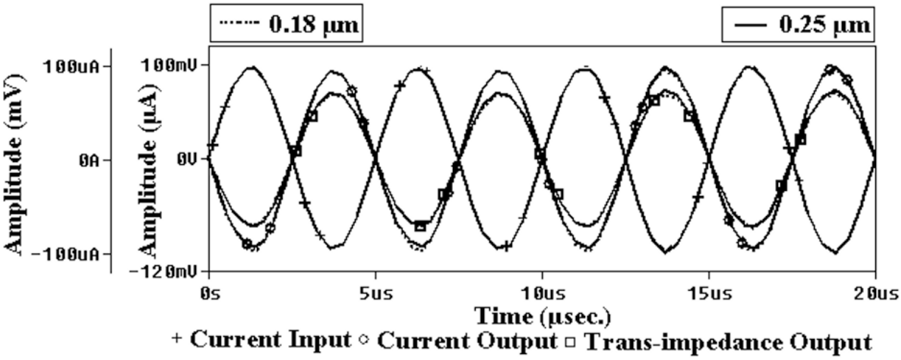


Fig. 12. The time domain sinusoidal current input of frequency 200 KHz and corresponding LP output waveforms in current and trans-impedance-mode, of the proposed filter simulated in 0.18µm and 0.25µm technology

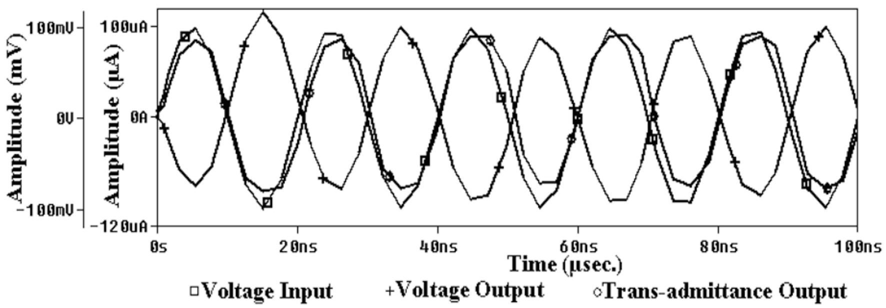


Fig. 13. The time domain sinusoidal voltage input of 50 MHz frequency and corresponding HP output waveforms in voltage and trans-admittance-mode, of the proposed filter

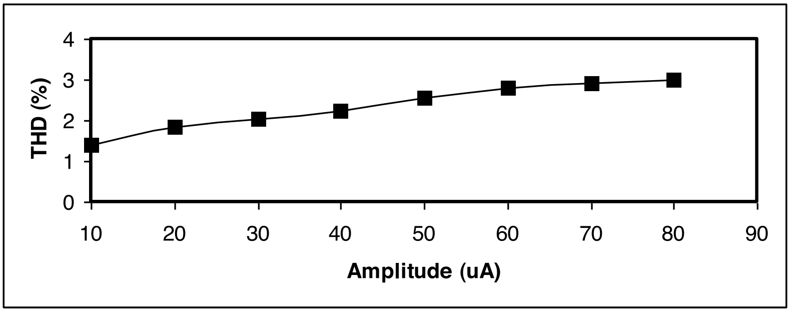
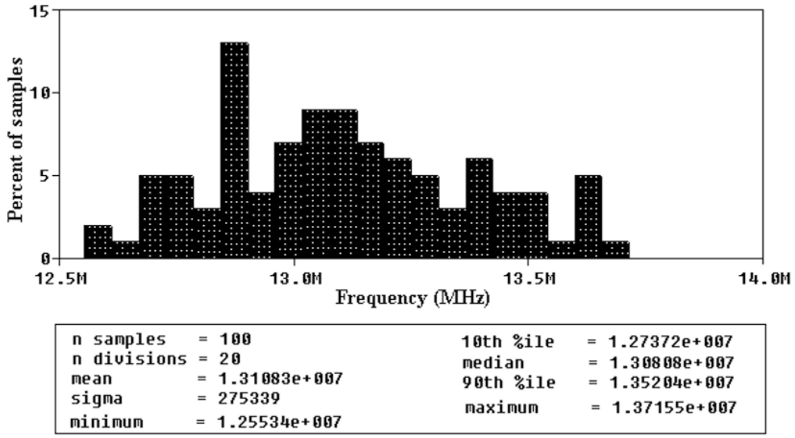


Fig. 14. THD for current-mode BP output at signal frequency of 12.02MHz



```
n samples    = 100                    10th %ile   = 1.27372e+007
n divisions  = 20                     median      = 1.30808e+007
mean         = 1.31083e+007           90th %ile   = 1.35204e+007
sigma        = 275339                 maximum     = 1.37155e+007
minimum      = 1.25534e+007
```

Fig. 15. The Monte-Carlo analysis performed on BP response in voltage-mode to measure the effect of capacitive deviations

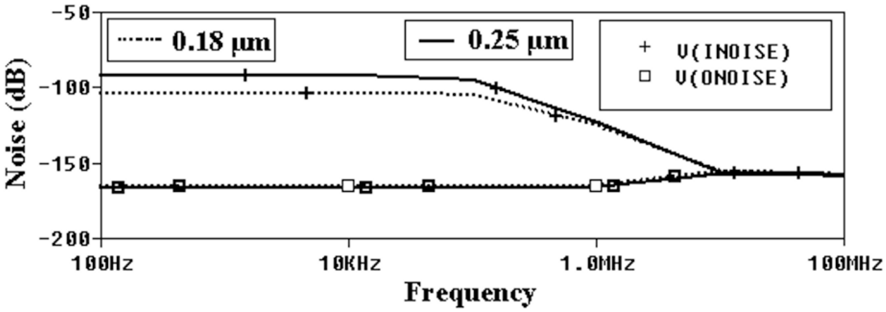


Fig. 16. The input and HP output voltage noise spectral density of the circuit of Figure 3

CONCLUSION

The work embodied in this paper presents an electronically tunable mixed-mode biquad universal filter using single MCCTA. The various transfer functions of the proposed filter and its characteristic parameters such as ω_0 and Q have been derived for ideal and non-ideal cases. To get a better insight into circuit's operability, simulations were carried out to ascertain the working of the proposed mixed-mode filters and results were found as per the theoretical expectations. Moreover, the proposed filter circuit offers the following advantages: (i) realizing LP, HP, BP, BR, and AP responses in current, trans-impedance, voltage-mode and trans-admittance-mode from the same circuit topology, (ii) low sensitivity performance, low THD and low power consumption, (iii) independent current control of Q without disturbing ω_o through single bias current, (iv) no requirements of inverted and double current/voltage input signal(s) for the circuit functionality, (v) use of only single active element consisting of only 31 MOS transistors which is less as compared to 38 MOS transistors used in already proposed single FDCCII based mixed-mode circuit in ref. (Lee *et al.*, 2009).

Apart from above advantages offered by the proposed circuit, a fair comparison of proposed work with similar type of works detailed in references cited, and are summarized in Table 2. The study of Table 2 reveals the following important points.

(i) The proposed mixed mode filter circuit requires only 31 MOS transistors and four passive elements, which are the least in term of active and passive components counts used among those of previously reported circuits (Table-2).

(ii) The circuits (Abuelma'atti *et al.,* 2004 and Zhijun, 2009) require ±2.5 V supply rails while (Chen *et al., 2*009) requires ±1.65 V supply rails in the design. Although, the circuits (Liao *et al*., 2011 and Lee *et al*., 2009) requires ±1.25 V supply rails, which is same as the power supply rails used to activate the proposed mixed mode circuit.

(iii) The proposed circuit is successfully designed for pole frequency of 12.02 MHz, which is highest in value among the previously similar type of existing circuits (Table-2), hence provides high frequency range of operation.

Hence, above discussion reveals that the proposed mixed mode circuits realizing five filtering responses in all four possible modes prove the superiority over similar type of existing design and can provide the optimum design solution in term of active and passive components counts, power supply requirement and the range of frequency operation.

Table 1. The Aspect ratio of MOS transistors in Figure 2

NMOS	**W(um)/L(um)**
M1- M2	2/0.25
M3 – M7, M10 – M11, M14 – M16	3/0.25
M8 – M9, M12 – M13	20/0.25
PMOS	**W(um)/L(um)**
M17 –M24, M26 - M28, M30 – M31	10/0.25
M25, M29	7.5/0.25

Table 2. Comparative study of previously reported Mixed-mode circuits with the proposed circuit

References	**Abuelma'atti *et al.* 2004**	**Liao *et al.*, 2011**	**Zhijun, 2009**	**Chen *et al.* 2009**	**Lee *et al.*, 2009**	**Proposed**
Active Element used	CCII	DDCCII	CCCII	OTA	FDCCII	MCCTA
Number of Active Element used	6	3	5	5	1	1
Number of Passive Element used	10	6	2	2	5	4
Use of Electronic Tunability	NO	NO	YES	YES	NO	YES
Supply Rails used	±2.5 V	±1.25 V	±2.5 V	±1.65 V	±1.25 V	±1.25 V
Designed Pole Frequency	0.5 MHz	3.98 MHz	638.5 KHz	1 MHZ	3.789 MHz	12.02 MHz
Total BJT/MOS Transistors required for implementation	-	54 MOS	75 BJTs	-	38 MOS	31 MOS
Realization of five filtering functions in all four modes	YES	YES	NO	YES	NO	YES
Providing electronic tunability feature of Q independent of ω_0	NO	NO	YES	YES	NO	YES

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