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A New Trans-admittance-Mode Biquad Filter Suitable for Low Voltage Operation

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ABSTRACT

The trans-admittance-mode (TAM) might act as a transforming bridge for voltage-mode to current-mode conversion. In this study a new low voltage operated electronically tunable TAM biquad filter structure realizing all the seven standard filtering functions namely; low-pass (LP), band-pass (BP), high-pass (HP), regular-notch (RN), low-pass-notch (LPN), high-pass-notch (HPN) and all-pass (AP) from the same configuration through appropriate selection of voltage input signals is presented. The proposed circuit structure comprises of three current conveyor trans-conductance amplifiers (CCTAs). Moreover, the new biquad filter structure still enjoys (i) realizations require neither inverted, nor scaled voltage input(s), (ii) the employment of two capacitors, hence providing canonical structure, (iii) the pole frequency can be tuned electronically, and (iv) possesses low incremental active and passive sensitivity performance and useful in low-voltage low-power applications. Personal simulation program with integrated circuit emphasis (PSPICE) simulation results using 0.25μm taiwan semiconductor manufacturing company (TSMC) complementary metal-oxide semiconductor (CMOS) parameters verify the theoretical analysis.

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1. INTRODUCTION

High performance continuous time filters operating in various modes [1-28] have received a lot of attention in analog signal processing applications. Among these, trans-admittance-mode filter [19-28] accept voltage input signal(s) and provides output current signal(s) and find applications in digital to analog converter (DAC), receiver base band blocks (RBB) of modern radio systems and optical receivers, etc. [20], where voltage signal to current signal transformation is vital. In the last few decades, designing of the filter topology suited for low voltage operation has gained much more attention because low voltage operating circuits consume less power and reduce the packing cost [29]. In this perspective, current-mode approaches are more preferable choice over voltage-mode approaches for the designing of low voltage operable electronic circuits [7], and hence, several current-mode active elements have been continuously proposed in the literature. Detail descriptions and classification of these elements was explained in [30]. Among them, CCTA is one which was formed by CCII followed by OTA and combines the features of CCII at its input stage and OTA at the output stage and offers the tuning feature by controlling trans-conductance parameter via biasing current. In addition, it can also offer number of advantages such as high slew rate, high speed, wider bandwidth and simpler implementation, associated with current-mode active elements [31-34]. All these advantages of CCTA can make it a promising choice as current-mode active element and hence, a number of active filters using CCTAs has been proposed in the available literature [14-18]. All the filter circuits realizing three [14] or more (four [18] or five [15-17]) filtering functions are either operated in current-mode [14-16] or voltage-mode [14, 17, 18] only and employ at least four (four [15-16], five [14-17], six [18]) number of active and passive elements. None of the CCTA based filter circuit reported in the available literature which is operated in the trans-admittance-mode. As far as the topic of the paper is concerned, realization of transadmittance-mode

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biquad filter is of special interest. However, literature survey also shows that quite a few trans-admittance-mode biquad filters based on different active elements other than CCTA have been reported in the available literature till date [20-28] whose features are summarized in Table 1. Among them, most of the filter circuits configurations operated in trans-admittance-mode are only under the single input three output (SITO) category [20-27] and bear one or more of the following deficit.

(i) Absence of electronic tunability feature [20-21, 26-27]

(ii) Excessive active and /or passive elements used [20-23, 25, 27].

(iii) Use of resistor(s) which occupies larger chip area [20-21, 27].

(iv) Incompetent to realize all possible seven standard filtering functions (LP, BP, HP, RN, LPN, HPN and AP) from the same configuration [20-27].

(v) Not operable at low voltage of ±1V particularly suited for low power low cost applications [20-23, 25-27].

However, only one trans-admittance-mode filter circuit of three input single output (TISO) category is found in the literature [28]. The filter circuit reported in [28] uses six active and passive elements (two CDTA, two floating resistors and two capacitors) and realizes only five standard filtering functions (LP, BP. HP, RN and AP). Moreover, it still requires ±3V supply rails. Considering the above facts, a new low voltage electronically tunable trans-admittance-mode filter with TISO configuration is proposed in this paper. The proposed configuration can realize BP, HP, LP, RN, and AP responses in trans-admittance-mode. Moreover, the realizations of LPN and HPN are also feasible from the same structure. The configuration comprises of only five active and passive elements (three CCTAs and two capacitors) and does not require: (i) external resistors which results in saving chip area, and (ii) inverted and/or double voltage input signal(s) to realize any filtering response. Besides, it is less sensitive to the employed active and passive components, and operated at ±1V (low voltage).

2. CURRENT CONVEYOR TRANS-CONDUCTANCE AMPLIFIER

The current conveyor trans-conductance amplifier, CCTA [32-34] is a recently incepted current-mode active element, which includes the features of second generation current conveyor and balanced output trans-conductance amplifier. It provides both high-impedance and low-impedance input terminals and offers suitability and flexibility to be operated in voltage-driven, current-driven and in hybrid-mode applications. The block diagram of CCTA is shown in Figure 1. It consists of two input terminals (X, Y). Input terminal X offers low impedance, whereas terminal Y offers high impedance. Port Z and port ±O are the high impedance output terminals.

As a single element CCTA can further be implemented using commercially available ICs, AD844 and MAX435 as per Figure 2. The property of CCTA in mathematical form is clearly delineated with Equation (1), while the circuit in Figure 3 shows the CMOS structure of CCTA.

$$I_Y = 0, V_X = V_Y, I_Z = I_X, I_{\pm O} = \pm g_m V_Z \tag{1}$$

In Equation (1), g_m is the trans-conductance parameter of CCTA. For the MOS implemented CCTA [**15**] the g_m can be derived as

$$g_m = \sqrt{\beta_n I_s} \tag{2}$$

where I_S is the biasing current of CCTA and β_n is the process parameter of NMOS transistors M_{12} and M_{13} and given by:

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

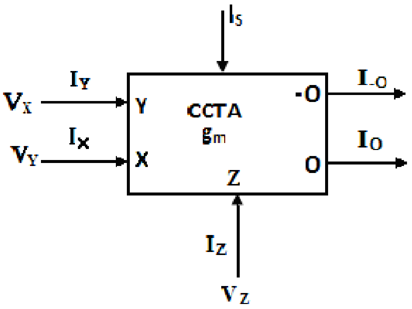


Figure 1. CCTA Symbol

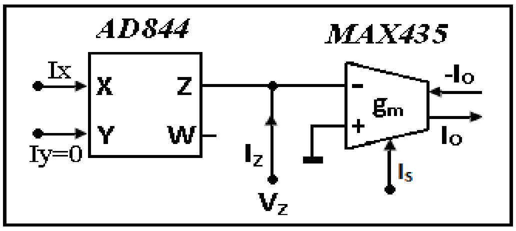


Figure 2. CCTA using commercially available ICs

TABLE 1. Comparison of previous different TAM filters with proposed circuit

Ref. **Features**	**[18]**	**[19]**	**[20]**	**[21]**	**[22]**	**[23]**	**[24]**	**[25]**	**[26]**	**Proposed**
Type of active elements used	3 CCII	3 FTFN	4 OTA	2 CCCCTA	2 VDTA	4 OTA	3 CCCII	5 DCC-DVCC	2 CDTA	3 CCTA
Type of passive elements used	3R, 2C	3R, 2C	2C	3 C	2C	2C	2C	2C , 1R	2R, 2C	2C
SITO/TISO	SITO	SITO	SITO	SITO	SITO	SITO	SITO	SITO	TISO	TISO
Operating pole frequency	22.5 MHz	15.9 KHz	0.884 MHz	277 KHz	< 2.5 MHz	3 MHz	1.27 MHz	500KHz-10MHz	159 KHz	6.31 MHz
Supply voltage used	± 12 V	NA	± 2.5 V	± 1.64 V	±0.9 V	± 2.5 V	± 1.5 V	± 1.25V	± 3 V	± 1 V
Responses realization	LP,BP,HP	LP,BP,HP	LP,BP,HP	LP,BP,HP, AP, BR	LP,BP,HP	LP,BP,HP	LP,BP,HP, AP, BR	LP,BP,HP	LP,BP,HP, AP,BR	LP,BP,HP, AP,BR
Electronic tunability	NO	NO	YES	YES	YES	YES	NO	NO	YES	YES

TABLE 2. Dimension of MOS for CCTA Implementation

NMOS	**W(μm)/L(μm)**
M1-M2	1/0.25
M3-M11	3/0.25
M12-M13	15/0.25
PMOS	**W(μm)/L(μm)**
M14-M25	5/0.25

3. PROPOSED TRANS-ADMITTANCE MODE FILTER CIRCUIT

The proposed filter circuit in Figure 4 is primarily designed with three CCTAs, and two capacitors (C_1, C_2). For the applied input voltage signals (V_{in1}, V_{in2}, and V_{in3}), the proposed circuit yields the following current output expression at I_{OUT}.

$$I_{OUT} = \frac{-g_{m1}(C_1C_2s^2V_{in3} - g_{m2}C_2sV_{in2} + g_{m2}g_{m3}V_{in1})}{C_1C_2s^2 + g_{m1}C_2s + g_{m1}g_{m2}} \tag{4}$$

From Equation (4), it is evident that through appropriate selection of V_{in1}, V_{in2}, and V_{in3} various biquad filtering responses in TAM-mode can be realized across I_{OUT}, as follows:

☐ With $V_{in1} = V_{in}$ and $V_{in2} = V_{in3} = 0$, the circuit provides LP response with gain (G_{LP}) = g_{m3}.

☐ With $V_{in2} = V_{in}$ and $V_{in1} = V_{in3} = 0$, the circuit provides BP response with gain (G_{BP})= g_{m2}.

☐ With $V_{in3} = V_{in}$ and $V_{in1} = V_{in2} = 0$, the circuit provides HP response with gain (G_{HP}) = g_{m1}.

☐ With $V_{in1} = V_{in3} = V_{in}$, $V_{in2} = 0$, the circuit provides **(1)** regular notch when $g_{m1} = g_{m3}$ **(2)** LPN when $g_{m1} < g_{m3}$ and **(3)** HPN when $g_{m1} > g_{m3}$.

☐ With $V_{in1} = V_{in2} = V_{in3} = V_{in}$ and $g_{m1}=g_{m2}=g_{m3}$, the circuit provides AP responses.

Above operational description clears that the proposed circuit configuration in Figure 4 is capable of realizing all possible seven biquad filtering responses in trans-admittance-mode without requiring inverting-type and/or double input voltage signal(s). The filter is further analyzed to determine the expression of characteristics parameters such as pole frequency (ω_0), quality factor (Q_0) and bandwidth (BW) as:

$$\omega_0 = \left(\frac{g_{m1}g_{m2}}{C_1C_2}\right)^{1/2} = \left(\frac{\beta_n}{C_1C_2}\right)^{1/2}(I_{S1}I_{S2})^{1/4} \tag{5}$$

$$Q_0 = \left(\frac{C_1g_{m2}}{C_2g_{m1}}\right)^{1/2} = \left(\frac{C_1}{C_2}\right)^{1/2}\left(\frac{I_{S2}}{I_{S1}}\right)^{1/4} \tag{6}$$

and

$$\text{BW} = \frac{\omega_0}{Q_0} = \frac{g_{m1}}{C_1} = \frac{(\beta_n I_{S1})^{1/2}}{C_1} \tag{7}$$

It can be remarked from Equations (5) and (6) that ω_0 can be tuned electronically without influencing quality factor by setting I_{S1}/I_{S2} to be a constant. Further, ω_0 can also be adjusted by I_{S2} without affecting filter's BW.

4. NON-IDEAL ANALYSIS

A non-ideal CCTA implemented with MOS transistors may be characterized by finite voltage, current and trans-conductance tracking errors occurred due to mismatching in the transistor's size and their parameters. Therefore, tracking errors effect on the filter's performance is also considered in this section. For this purpose, the relationship of the terminals voltage and current of the CCTA with involved non-idealities can be modified as given by the following set of equations.

$$V_X = \beta_i V_Y,\ \ I_Z = \alpha_i I_X,\ \ I_{\pm O} = \pm\,\gamma_i\, g_m\, V_Z \tag{8}$$

where β_i, α_i , and γ_i are the signal tracking errors from terminals Y → X, X → Z and Z → O or Z →-O, respectively of i^{th} CCTA (i=1,2,3) which may be deviated from unity. Taking above non-idealities into consideration, if we reanalyzed the circuit in Figure 4, the following current output expression can be obtained.

$$I_{OUT} = \frac{\begin{array}{c}-\gamma_1 g_{m1}(C_1C_2s^2V_{in3} - g_{m2}C_2sV_{in2} \\ +\alpha_2\alpha_3\beta_2\gamma_3 g_{m2}g_{m3}V_{in1})\end{array}}{C_1C_2s^2 + \alpha_1\gamma_1 g_{m1}C_2 s + \alpha_1\alpha_2\gamma_1 g_{m1}g_{m2}} \tag{9}$$

Now the filter parameters such as ω_0, Q_0 and BW of the proposed circuit with involved non ideal tracking errors are changed to:

$$\omega_0 = \left(\frac{\alpha_1\gamma_1\alpha_2 g_{m1}g_{m2}}{C_1C_2}\right)^{1/2}, Q_0 = \left(\frac{\alpha_2 C_1 g_{m2}}{\alpha_1\gamma_1 C_2 g_{m1}}\right)^{1/2} \tag{10}$$

and

$$\mathrm{BW} = \frac{\alpha_1\gamma_1 g_{m1}}{C_1} \tag{11}$$

It can be noticed from Equations (9) - (11) that slight deviations are expected in pass band gains of the various filter responses and filter parameters due to effects imposed by current tracking errors of CCTAs. However, these slight digressions can be easily regulated by renew the biasing currents I_{S1} and I_{S2}. Sensitivity analysis of the proposed filter with respect to active and passive elements yields:

$$\begin{gathered} S^{\omega_0}_{\alpha_1} = S^{\omega_0}_{\alpha_2} = S^{\omega_0}_{\gamma_1} = S^{\omega_0}_{g_{m1}} = S^{\omega_0}_{g_{m2}} = \frac{1}{2}, \\ S^{\omega_0}_{C_1} = S^{\omega_0}_{C_2} = -\frac{1}{2}, S^{\omega_0}_{\alpha_3,\gamma_2,\gamma_3,\beta_1,\beta_2,\beta_3} = 0 \end{gathered} \tag{12}$$

$$\begin{gathered} S^{Q_0}_{\alpha_2} = S^{Q_0}_{C_1} = S^{Q_0}_{g_{m2}} = \frac{1}{2}, S^{Q_0}_{\alpha_1} = S^{Q_0}_{\gamma_1} = S^{Q_0}_{g_{m1}} = S^{Q_0}_{C_2} = -\frac{1}{2}, \\ S^{Q_0}_{\alpha_3,\gamma_2,\gamma_3,\beta_1,\beta_2,\beta_3} = 0 \end{gathered} \tag{13}$$

Equations (12) and (13) wrap up the active and passive sensitivities of the proposed filter for ω_0, and Q_0 within half in magnitude.

5. SIMULATION RESULTS

The functionality of the proposed trans-admittance-mode biquad filter has been verified by performing P-SPICE simulations with V_{DD} = -V_{SS} = 1 V, V_{BB} = -0.5 V and using CMOS TSMC 0.25μm technology parameters [35]. The CMOS implementation of CCTA as depicted in Figure 3 is used for simulation purpose. The dimensions (W and L) of various MOS transistors are determined, as specified in Table 2. The proposed circuit in Figure 4 is designed to obtain f_0 = 6.28 MHz, Q_o=1, by choosing active and passive components as I_{S1} = I_{S2} = I_{S3} = 32μA, C_1 = C_2 = 17pF. For the above designed specifications, the proposed circuit consumes a low power of 0.85mW.

In Figure 5, the gain and phase responses of BP, HP, LP, RN and AP of the proposed TAM filter are depicted. The pole frequency measured from simulation results in Figure 5 is 6.31 MHz, which is fairly closed to the designed value of 6.28 MHz. This deviation in pole frequency is primarily due to involved non-idealities such as non-ideal gain and involved parasitic elements. The proposed circuit is also simulated to get LPN and HPN.

Figures 6 and 7 show the trans-admittance gain responses of LPN and HPN, respectively. LPN is realized with the components value as I_{S1} = 15μA, I_{S2} = 32μA, I_{S3} = 32μA, and C_1 = C_2 = 17pF while, HPN is realized with the components value as I_{S1} =19μA, I_{S2} = 80μA, I_{S3} = 5μA, and C_1 = C_2 = 17pF. The electronic tuning aspect of pole frequency independent of quality factor is also shown in Figure 8, by performing the simulations of gain and phase responses for RN at different values of I_{S1} = I_{S2} = I_{S3} = Is = 20μA, 32μA, 60μA, 200μA, which results in pole frequency variation from 4.16 MHz to 12.14 MHz without influencing Q. Furthermore, the transient behavior for HP response on applying a sinusoidal input voltage signal of 240mV peak to peak amplitude and at a frequency of 150 MHz is shown in Figure 9.

It can be noticed from the response that input signal of aforesaid amplitude and frequency range is possible without substantial distortions. In succession, to observe the effect of passive component mismatching on the filter's performance, Monte-Carlo analysis has been performed for 100 samples. For this, the BP filter was simulated by setting the values of capacitors C_1 and C_2 with 5% Gaussian deviation.

The statistical results in histogram are shown in Figure 10 where the simulated mean, median and standard deviations were found as 7.21 MHz, 7.19 MHz and 147.81 KHz, respectively. It reveals that the proposed filter with respect to the simulated pole frequency of 6.31 MHz is less sensitive to the changes in capacitors value and thus offers reasonable passive sensitivity.

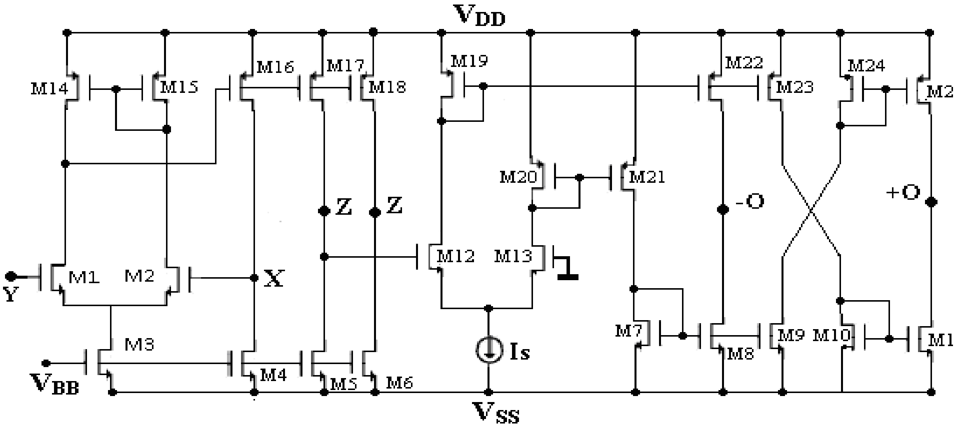


Figure 3. MOS implementation of CCTA

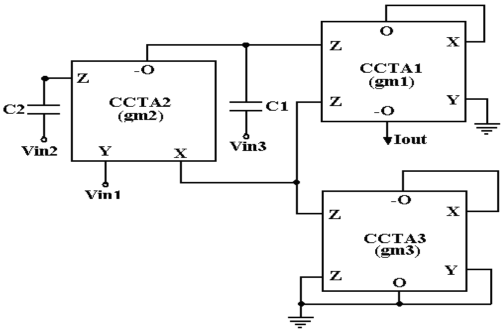
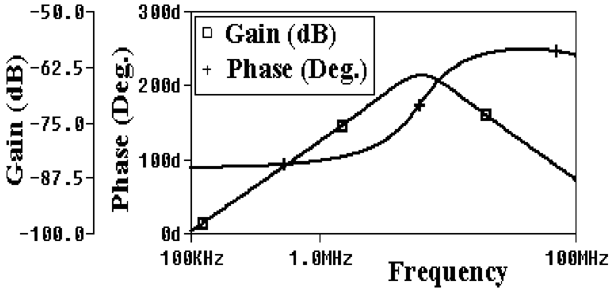
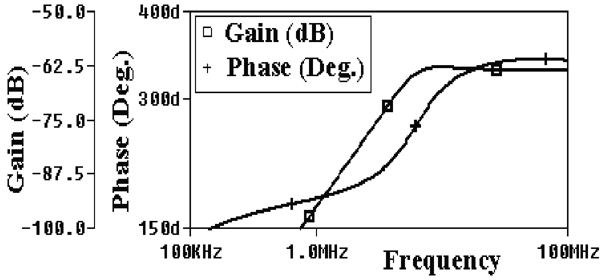


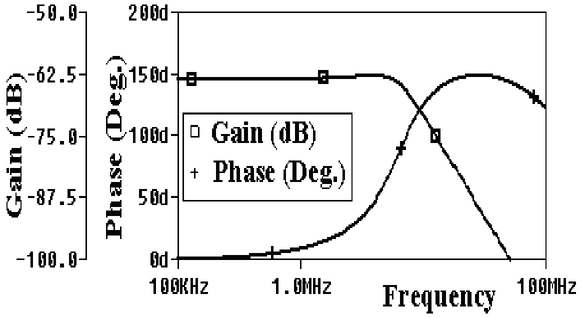
Figure 4. Proposed TAM universal biquad filter



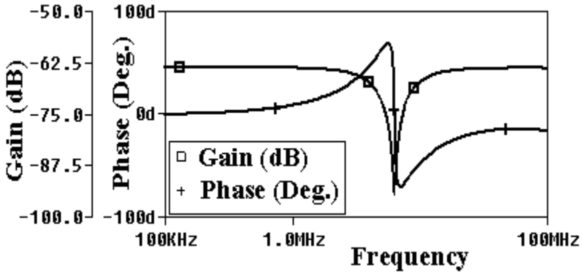
(a)



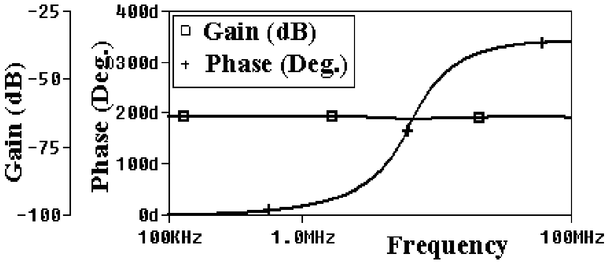
(b)



(c)



(d)



(e)

Figure 5. TAM-mode gain and phase responses of (a) BP (b) HP (c) LP (d) RN and (e) AP for the proposed filter circuit in Figure 4

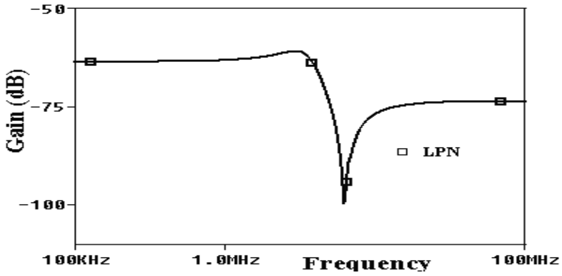


Figure 6. TAM-mode gain response of LPN for the proposed filter circuit in Figure 4

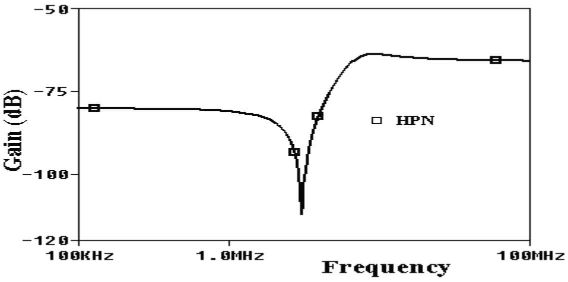


Figure 7. TAM-mode gain response of HPN for the proposed filter circuit in Figure 4

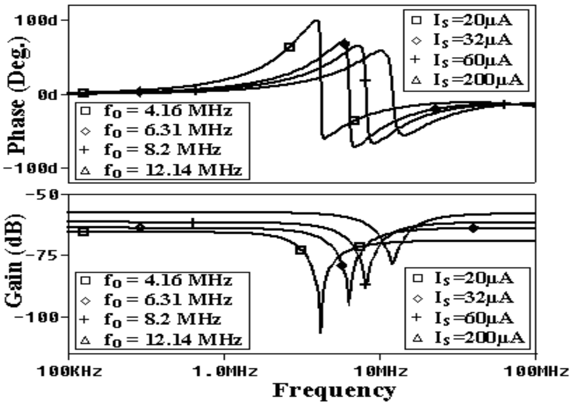


Figure 8. Pole frequency electronic tuning for the proposed filter circuit in Figure 4

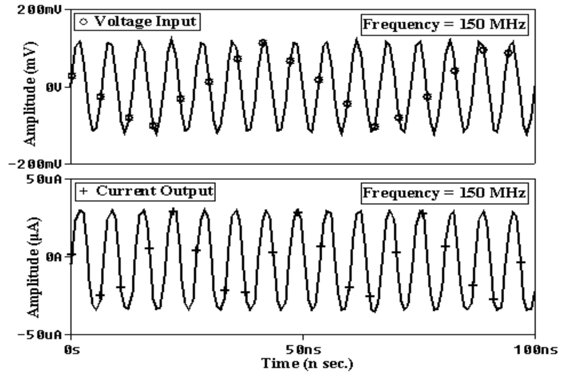
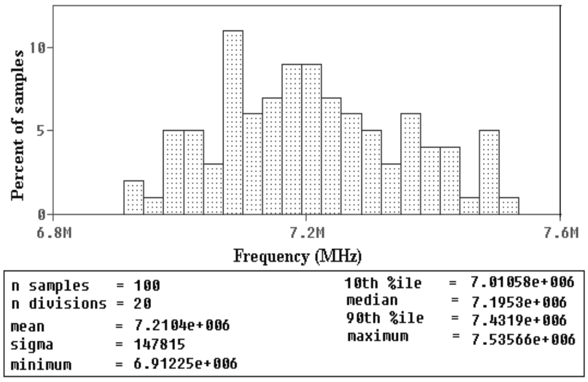


Figure 9. Transient response of TAM-mode HP filter with sinusoidal voltage input signal of frequency 150MHz



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n samples    = 100                10th %ile   = 7.01058e+006
n divisions = 20                  median      = 7.1953e+006
mean         = 7.2104e+006        90th %ile   = 7.4319e+006
sigma        = 147815             maximum     = 7.53566e+006
minimum      = 6.91225e+006
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Figure 10. Statistical results of Monte-Carlo analysis for the BP response of proposed circuit with 5% deviation in the capacitor values

6. CONCLUSIONS

In this paper, a new proposal of biquad filter topology realizing seven filtering functions in trans-admittance mode is discussed which comprises of only three CCTAs and two capacitors. It uses neither external resistor(s), nor inverted/scaled-type input voltage signal(s) for the filtering function realizations. In addition to these features, the circuit also enjoys few more advantages such as: (i) low sensitivity figures for ω_0 and Q_0, (ii) operability of the circuit at low voltage power supply, (iii) offering electronic tunability feature of ω_0 independent of Q_0, and (iv) low power consumption of 0.85mW, and (v) providing a canonical structure. However, it is well known that nothing is perfect and complete in this life; so, this circuit has also few limitations of: (i) employing the floating capacitors, (ii) non availability of two of input voltage signals (V_{in2}, V_{in3}) at low impedance level (iii) providing only interactive current tuning of filter parameters (i.e. doesn’t have non interactive tuning) but these limitations are justified in light of realization of all possible seven TAM filtering functions by the proposed circuit and also operated at low power supply voltage of ±1V [36]. Moreover, the new TAM biquad filter structure provide advancement to the existing knowledge with the future scope of the proposed topology being further exploited for improving the above limitations and practical implementation.

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A New Trans-admittance-Mode Biquad Filter Suitable for Low Voltage Operation

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چکیده

ترانس حالت عبوری (TAM) می‌تواند به عنوان یک پل برای تبدیل حالت ولتاژ به تبدیل حالت جریان عمل کند. در این مطالعه یک فیلتر جدید کم ولتاژ TAM الکترونیکی با ساختار biquad با استفاده از تمام هفت نوع تابع استاندارد فیلتر یعنی: پایین گذر(LP) ، باند گذر (BP)، بالا گذر (HP) ، شکاف معمولی (RN)، شکاف معمولی پایین گذر (LPN)، شکاف معمولی بالا گذر (HPN) و تمام گذر (AP) از همان پیکربندی از طریق انتخاب مناسب سیگنال‌های ورودی ولتاژ ارائه شده است. ساختار مدار پیشنهادی شامل سه ترانس تقویت جریان (CCTAs است. علاوه بر این، ساختار فیلتر biquad جدید: (۱) نه نیاز به معکوس کردن، و نه کوچک کردن ولتاژ ورودی (۲) به کارگیری دو خازن، و از این رو فراهم ساختن ساختار متعارف مخروطی، (۳) امکان تنظیم الکترونیکی فرکانس قطب، و(٤) دارا بودن حساسیت فعال و غیر فعال کم و مفید در برنامه های کاربردی ولتاژ و قدرت پایین است. نتایج شبیه سازی PSPICE با استفاده از پارامترهای ۰ CMOS TSMC μm ۲۵ /۰ تحلیل نظر را تایید می‌کند.

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