New CMOS Realization of Voltage Differencing Buffered Amplifier and Its Biquad Filter Applications

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Abstract. *In this paper, new biquad filter configuration using a recently introduced active element, namely Voltage Differencing Buffered Amplifier (VDBA), is proposed. This block has high impedance input terminals and low impedance output terminal, providing advantages at voltage mode circuits. Besides, VDBA has a transconductance gain, thus the proposed circuits can be employed without using any external resistors. Two new voltage-mode biquad filter configurations are presented for VDBA application. Each proposed filter employs two active elements and two or three passive components. Filters, having three inputs and single output, can realize voltage-mode low-pass, band-pass, high-pass, band-stop, and all-pass filters. The biquad filters have low output impedances that is necessary for cascadability for voltage mode circuits, and no critical component matching conditions are required. For the second biquad, quality factor can be adjusted via resistor independently of the natural frequency. Simulation results are given too, confirming the theoretical analysis. The proposed biquad filters are simulated using TSMC CMOS 0.35 μm technology. LTSPICE simulations of the proposed circuits give results that agree well with the theoretical analysis.*

Keywords

Voltage differencing Buffered Amplifier, voltage mode filter, CMOS integrated circuit.

1. Introduction

Different kind of active elements have been used in second order active filters up to now. A number of analog signal processing circuits have been proposed utilizing assorted active elements. Many active elements able to function such as Operational Transconductance Amplifier (OTA) [1] and Current Differencing Transconductance Amplifier (CDTA) [2] have also played an important role, specifically Operational Transresistance Amplifier (OTRA) [3], Current Differencing Buffered Amplifier (CDBA) [4], First Generation Current Conveyor (CCI) [5] and Fully Balanced Voltage Differencing Buffered Amplifier (FB-VDBA) [6]. In [7], the circuit principle called VDBA (Voltage Differencing Buffered Amplifier) is proposed as an alternative to the existing CDBA (Current Differencing Buffered Amplifier). The differences between VDBA and CDBA are that the VDBA inputs are voltage as for the CDBA inputs are current.

Besides, VDBA can be compared with OP-AMP. Both of them have the same properties such as high input and low output impedances. Differential input voltage is transferred to current at the terminal Z by transconductance gain and the voltage drop at the terminal Z is mirrored in different impedance region, that is, terminal W. However, VDBA provides properties of current mode circuit such as greater bandwidth, lower power consumption, higher slew rate and wider linearity compared to OP-AMP [8]-[9]. Furthermore, VDBA still enjoys features of transconductances such as value of transconductance can be adjusted electronically, proposed circuits can be employed without using external resistor. Besides, difference between VDBA and OTA is that VDBA has low output impedance that is more suitable than voltage-mode circuit because loading effect is completely eliminated.

In the proposed voltage mode transconductance-based TISO filtering circuits, the circuits [10]-[18] enjoy adjusting natural frequency and quality factor with biasing voltages/currents, no need to external resistors, and low sensitivities. However, the reported filters suffer from one or more of the following disadvantages;

I. they need a large number of active components [11]-[16],

II. they use two kinds of active components [11], [16],

III. some filter response requires the component-matching conditions [10], [12]-[14],

IV. they are not suitable for voltage mode filter structure due to high output impedances (good for cascadability) [10]-[15], [17], [18],

V. quality factor cannot be adjusted as independent frequency [10]-[12], [15], [17], [18].

In this paper, a new CMOS realization of voltage differencing buffered amplifier (VDBA) is given and two new voltage-mode biquad filters have been presented. Both of circuits contain two VDBAs, two or three passive components and have three-inputs single-output. The first proposed biquad filter contains two VDBAs and two capacitors and generates all filter functions (low-pass (LP), band-pass (BP), high-pass (HP), band-stop (BS) and all-pass (AP)), but this topology needs inverting type input voltage signal for the employed AP filters. The second proposed biquad filter employs two VDBAs, two capacitors and a resistor and realizes the all filter functions without the use of inverting input terminals. Furthermore, quality factor can be adjusted with resistor as independent natural frequency. Besides this resistor can be realize with NMOS transistors, thus quality factor can be tuned electronically with gate voltage [19].

In addition to these features, thank to transconductance gain of VDBA, natural frequency or quality factor of these biquad filters can be adjusted electronically, each of the proposed circuits still enjoy realization using a minimum number of active and passive components, and no requirement with the component choice conditions to realize specific filtering functions and have low passive sensitivity.

2. Proposed VDBA-Based Filter Circuits

The proposed schematic symbol of the VDBA is in Fig. 1, in which P and N are input terminals, Z and W are output terminals.

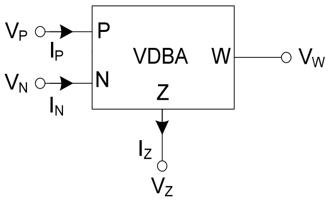

Fig. 1. The circuit symbol of the VDBA.

The model can be described by the following set of circuit equations;

$$\begin{pmatrix} I_P \\ I_N \\ I_Z \\ V_W \end{pmatrix} = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ g_m & -g_m & 0 \\ 0 & 0 & \alpha \end{pmatrix} \begin{pmatrix} V_P \\ V_N \\ V_Z \end{pmatrix} \tag{1}$$

where α is the voltage ratio of VDBA and $\alpha = 1\text{-}\varepsilon_v$. Here, ε_v is the voltage tracking error. The magnitude of tracking error is much less than unity. It should be noted from the above that Voltage Differencing Buffered Amplifier (VDBA) has a pair of high-impedance voltage inputs V_P and V_N, high-impedance current outputs I_Z and low-impedance voltage outputs V_W.

Fig. 2 shows the complete schematic of the proposed VDBA circuit, which is based on the use of the OTA circuit (M_1-M_9) [20] and the voltage buffer (M_{10}-M_{16}) [21]. The input stage of VDBA is composed of the differential-input OTA. The voltage buffer is connected to the OTA current output. The operational transconductance amplifier (OTA) is an amplifier whose differential input voltage produces an output current is a voltage controlled current source (VCCS). There is usually an additional input for current to control the amplifier's transconductance. The OTA is similar to a standard operational amplifier in that it has a high impedance differential input stage and is suitable for negative feedback. A buffer amplifier (sometimes simply called a buffer) is one that provides electrical impedance transformation from one circuit to another.

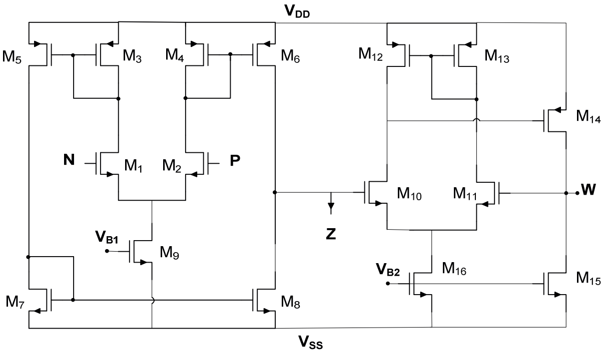

Fig. 2. CMOS implementation of the VDBA.

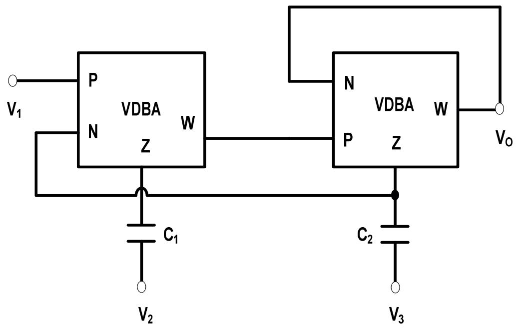

Fig. 3. The first proposed biquad filter.

The first proposed circuit that can be used as three-inputs single-output voltage-mode filter is shown in Fig. 3. The node analyses of circuit in Fig. 3 yield the following voltage transfer function

$$V_O = \frac{V_3 s^2 C_1 C_2 \alpha_2 + V_2 s g_{m2} C_1 \alpha_1 \alpha_2 + V_1 g_{m1} g_{m2} \alpha_1 \alpha_2}{s^2 C_1 C_2 + s g_{m2} C_1 \alpha_2 + g_{m1} g_{m2} \alpha_1}. \tag{2}$$

Depending on the voltage status of V_1, V_2 and V_3 in the numerator of equation (2), one of the following five filter functions are realized;

(i) LP : $V_2 = V_3 = 0, V_1 = V_{IN}$
(ii) BP : $V_1 = V_3 = 0, V_2 = V_{IN}$
(iii) HP : $V_1 = V_2 = 0, V_3 = V_{IN}$
(iv) BS : $V_2 = 0, V_1 = V_3 = V_{IN}$
(v) AP : $V_1 = V_3 = \text{-}V_2$

The pole frequency (ω_o) and quality factor (Q) of the first proposed biquad filter are given as follows;

$$\omega_O = \sqrt{\frac{g_{m1} g_{m2} \alpha_1}{C_1 C_2}}\,, \tag{3}$$

$$Q = \frac{1}{\alpha_2}\sqrt{\frac{g_{m1} C_2 \alpha_1}{g_{m2} C_1}}\,. \tag{4}$$

Sensitivity analyses of the proposed filters with respect to active and passive elements yield;

$$S_{g_{m1}}^{\omega_0} = S_{g_{m2}}^{\omega_0} = -S_{C_1}^{\omega_0} = -S_{C_2}^{\omega_0} = S_{\alpha_1}^{\omega_0} = \frac{1}{2},\ \ S_{\alpha_2}^{\omega_0} = 0. \tag{5}$$

$$S_{g_{m1}}^{Q} = -S_{g_{m2}}^{Q} = -S_{C_1}^{Q} = S_{C_2}^{Q} = S_{\alpha_1}^{Q} = \frac{1}{2},\ \ S_{\alpha_2}^{Q} = -1. \tag{6}$$

It is clearly observed that active and passive sensitivities of ω_o and Q do not exceed unity.

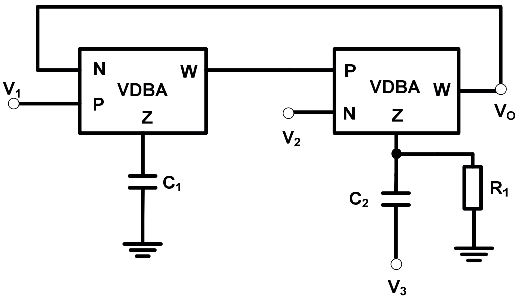

Fig. 4. The second proposed biquad filter.

The second proposed biquad filter is shown in Fig. 4. Its transfer function can be given as

$$V_O = \frac{V_3 s^2 C_1 C_2 \alpha_2 - V_2 s C_1 g_{m2} \alpha_2 + V_1 g_{m1} g_{m2} \alpha_1 \alpha_2}{s^2 C_1 C_2 + \dfrac{s C_1}{R_1} + g_{m1} g_{m2} \alpha_1 \alpha_2}\,. \tag{7}$$

It can be seen from (7) that the proposed filter can be obtained five types of standard biquad filter, those are summarized as follows:

(i) LP : $V_2 = V_3 = 0, V_1 = V_{IN}$
(ii) BP : $V_1 = V_3 = 0, V_2 = V_{IN}$
(iii) HP : $V_1 = V_2 = 0, V_3 = V_{IN}$
(iv) BS : $V_2 = 0, V_1 = V_3 = V_{IN}$
(v) AP : $V_1 = V_3 = V_2 = V_{IN}$

The pole frequency (ω_o) and quality factor (Q) of the second proposed biquad filter are given as follows:

$$\omega_O = \sqrt{\frac{g_{m1} g_{m2} \alpha_1 \alpha_2}{C_1 C_2}}\,. \tag{8}$$

$$Q = R_1\sqrt{\frac{g_{m1} g_{m2} C_2 \alpha_1 \alpha_2}{C_1}}\,. \tag{9}$$

Clearly, the Q can be tuned by different resistor values as independent natural frequency. Moreover, R_1 can be employed with NMOS transistors and can be adjusted electronically through the control voltages. Sensitivity analyses of the proposed filters with respect to active and passive elements yield

$$S_{g_{m1}}^{\omega_0} = S_{g_{m2}}^{\omega_0} = -S_{C_1}^{\omega_0} = -S_{C_2}^{\omega_0} = S_{\alpha_1}^{\omega_0} = S_{\alpha_2}^{\omega_0} = \frac{1}{2},\ \ S_{R_1}^{\omega_0} = 0\,, \tag{10}$$

$$S_{g_{m1}}^{Q} = S_{g_{m2}}^{Q} = -S_{C_1}^{Q} = S_{C_2}^{Q} = S_{\alpha_1}^{Q} = S_{\alpha_2}^{Q} = \frac{1}{2},\ \ S_{R_1}^{Q} = 1\,. \tag{11}$$

It is clearly observed from (10) and (11) that active and passive sensitivities of ω_o and Q do not exceed unity.

3. Simulation Results

Finally, a possible CMOS realization of a VDBA element is given in Fig. 2 to verify the theoretical prediction of the proposed biquad filters. We perform the simulation by using LTSPICE program with TSMC CMOS 0.35 μm technology. The supply and bias voltages are given by $V_{DD} = -V_{SS} = 1.5$ V and $V_{B1} = -0.44$ V, $V_{B2} = -0.9$ V. The aspect ratios of the transistors are shown in Tab. 1. Simulation results show that this choice yields the transconductance value of $g_m = 748$ μA/V for the VDBA and parasitic impedances of $R_{Zp} = 315$ kΩ, $C_{Zp} = 0.32$ pF and $R_{Wp} = 21$ Ω, parasitic parallel resistances and capacitances at Z terminal and parasitic series resistances at W terminal, respectively. The power consumption of the proposed VDBA is 0.97 mW.

Transistors	W(μm)	L(μm)
M_1-M_4, M_{10}, M_{11}, M_{15}, M_{16}	7	0.35
M_5, M_6	21	0.7
M_7, M_8	7	0.7
M_9	3.5	0.7
M_{12}-M_{14}	14	0.35

Tab. 1. Transistors aspect ratios for the VDBA.

The main DC and AC characteristics of VDBA, such as plots of I_Z against V_P, plots of V_Z against V_W, frequency responses of I_Z/V_P and V_W/V_Z are obtained from LTSPICE simulations and given in Figs. 5-8.

The DC transfer characteristic of I_Z against V_P for VDBA is shown in Fig. 5 that is obtained when one input (terminal N) is grounded. $V_Z - V_W$ DC characteristics of the VDBA is shown in Fig. 6. While the upper boundary of the voltage V_W for VDBA is determined as $V_{Wmax} = 1.1$ V, the lower boundary of voltage V_W for VDBA is the negative supply voltage of the VDBA.

The frequency response of transconductance value of the input stage and the frequency response of output stage are shown in Fig. 7 and Fig. 8, respectively.

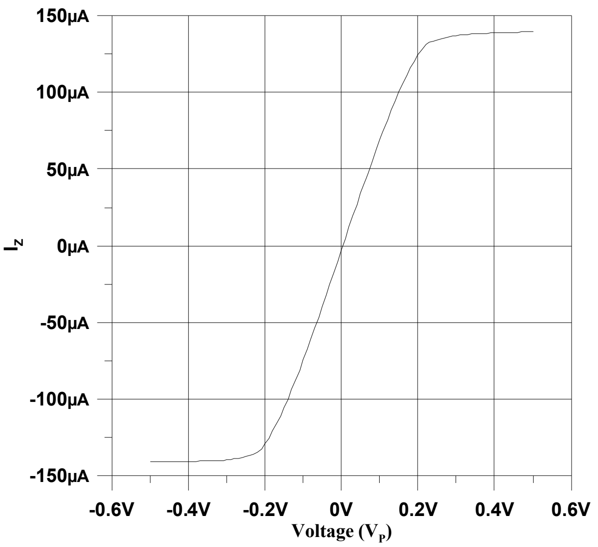

Fig. 5. The DC transfer characteristic of input stage of the VDBA.

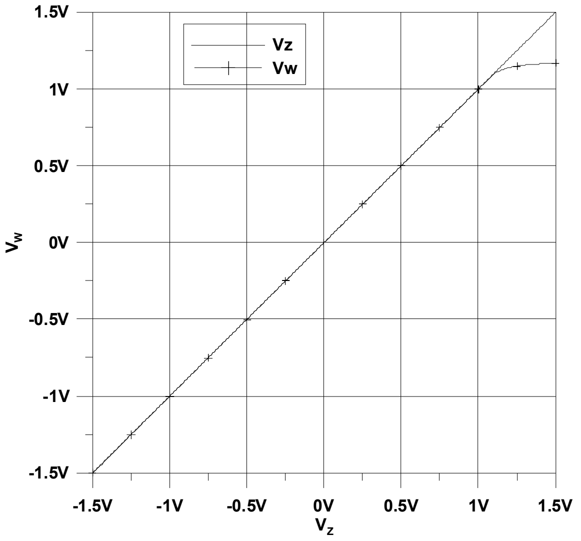

Fig. 6. The DC transfer characteristic of output stage of the VDBA.

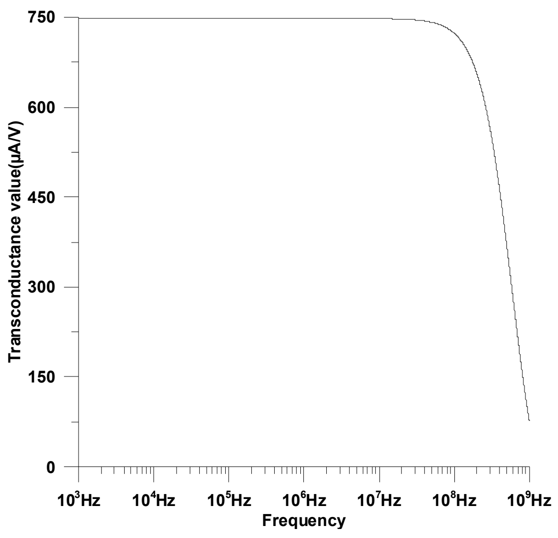

Fig. 7. The AC transfer characteristic of input stage of the VDBA.

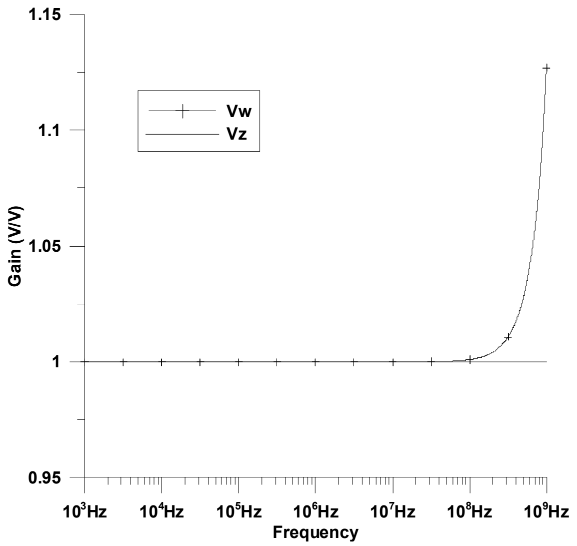

Fig. 8. The AC transfer characteristic of output stage of the VDBA.

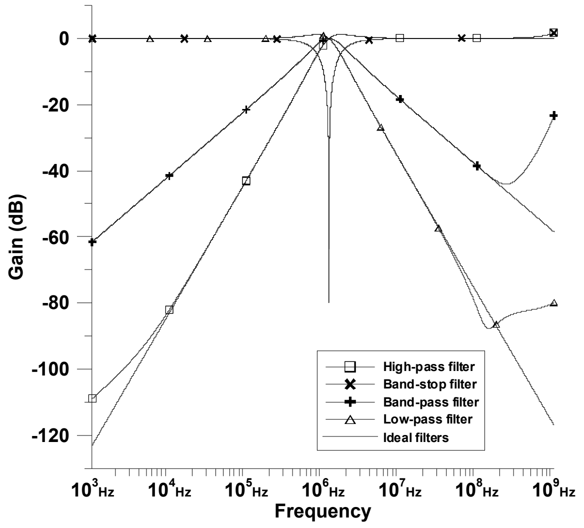

Fig. 9. The simulated results of the gain–frequency responses of Fig. 3.

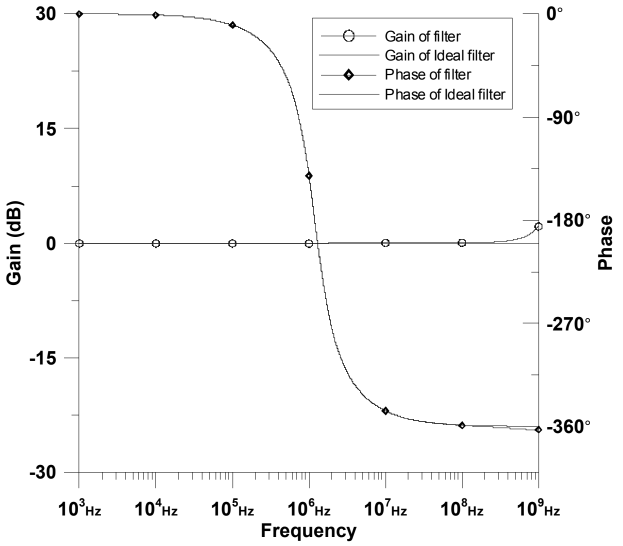

Fig. 10. Gain and phase-frequency responses of all pass filter in Fig. 3.

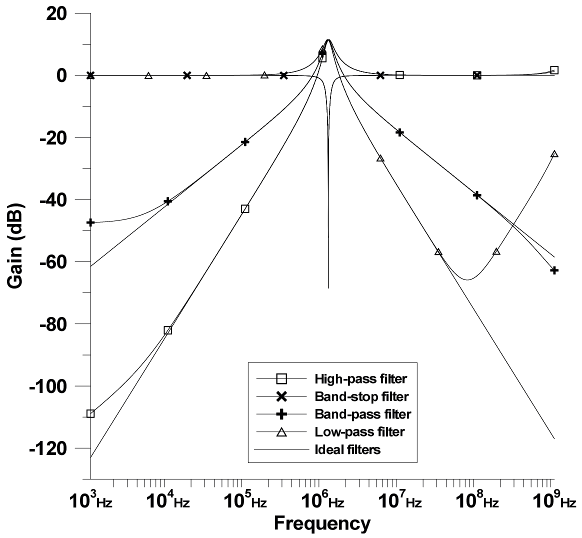

Fig. 11. The simulated results of the gain–frequency responses of Fig. 4.

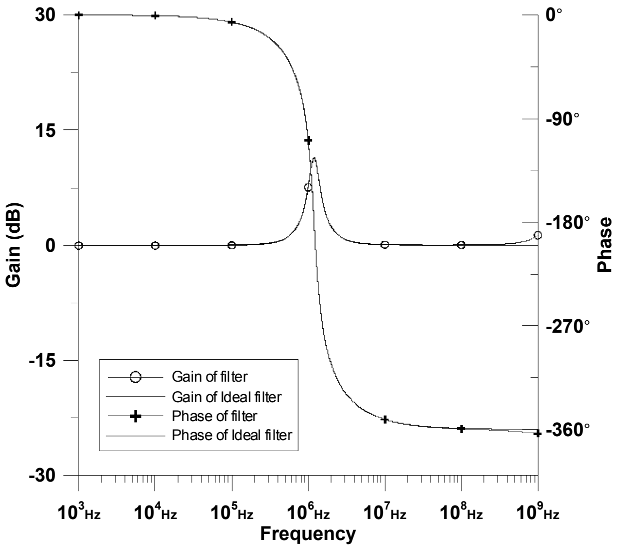

Fig. 12. Gain and phase-frequency responses of all pass filter in Fig. 4.

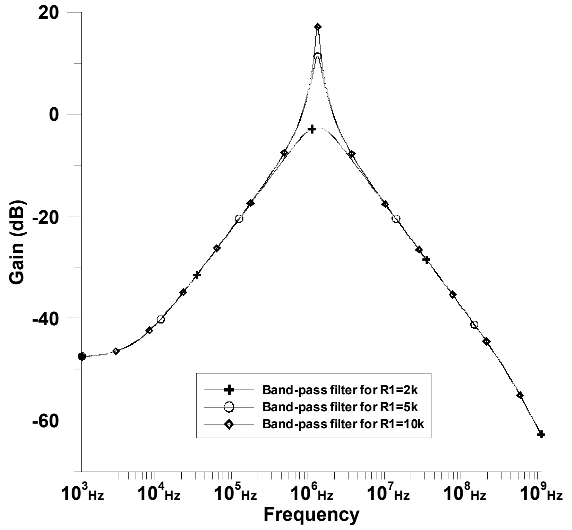

Fig. 13. Tuning property with different values of resistor of VDBA based biquad filter in Fig. 4.

The measured frequency responses of the biquad filters are compared with results of LTSPICE AC analysis in Fig. 9. The curves also include a gain drop on the input block of the impedance matching. These results correspond well with the design intentions. The roll-off effect of the high-pass section near 100 MHz is caused by the frequency limitations of dimensions transistors. The voltage-mode biquad filter in Fig. 3 was designed for f_o = 1.19 MHz and a quality factor of Q = 1 by choosing $g_{m1} = g_{m2}$ = 748 μA/V and $C_1 = C_2$ = 100 pF. Simulated responses of low-pass, band-pass, high-pass and band-stop filters are shown in Fig. 9. Gain and phase frequency responses of all-pass filter are given in Fig. 10.

The simulated frequency responses of LP, BP, HP and BS filter characteristics of the second proposed configurations are given in Fig. 11. For the simulations, equal capacitance values of $C_1 = C_2$ = 100 pF, trans-conductance gain values of $g_{m1} = g_{m2}$ = 748 μA/V and R_1 = 5k are chosen for a natural angular frequency of f_0 = 1.19 MHz and a quality factor of Q = 3.75. Fig. 12 illustrates the simulated gain and phase responses of the AP characteristic of the second proposed configuration with the same chosen component values. Fig. 13 exhibits the quality factor tuning properties of the VDBA-based band-pass filter given in Fig. 4. It is obvious from the curves that, as deduced above, tuning of Q can be performed via different resistor values.

The large signal behavior of the proposed circuit band-pass filter of Fig. 3 is tested by applying a 1 MHz sinusoidal signal with amplitude of 0.2 V to the input. The simulated transient response of the filter is given in Fig. 14. The dependence of the output harmonic distortion of band-pass filter on input voltage amplitude is illustrated in Fig. 15. The harmonic distortion slowly increases depending input voltage and for an input lower than 400 $mV_{p\text{-}p}$, the THD remains in acceptable limits i.e. 1 % thus confirming the practical utility of the proposed circuit shown in Fig. 15.

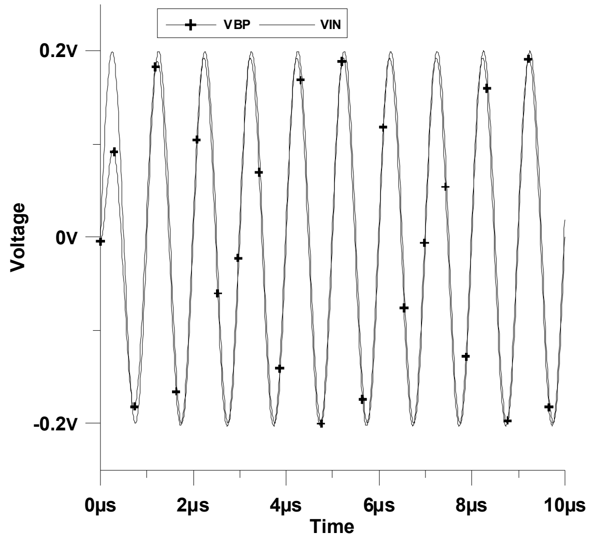

Fig. 14. The input and output waveforms of the proposed circuit band-pass filter of Fig. 3 for 1 MHz sinusoidal input voltage of 0.4 V peak to peak.

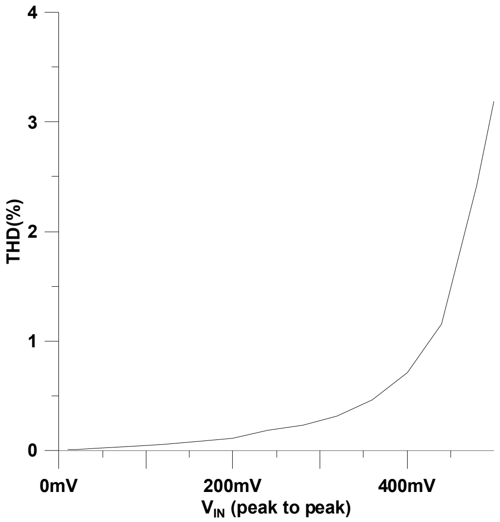

Fig. 15. Total harmonic distortion (THD) values of Fig. 3 for different frequency values terminals.

4. Conclusion

In this paper, a new CMOS implementation of voltage differencing buffer amplifier is presented and two proposed voltage-mode three-input single-output biquad filters containing two VDBAs and two or three passive components. Both filter circuits realize all filter configurations and natural frequency can be tuned electronically with bias voltage. Furthermore, quality factor of the second proposed filter can be adjusted to resistor as independent natural frequency. All circuits also require no component matching conditions so they are suitable for IC technology providing the output voltage signal at low impedances in this way facilitating cascadability feature to voltage mode circuits. Moreover, each of proposed circuit still enjoys use of minimum passive elements, low passive sensitivity and acceptable THD value range.

Acknowledgments

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