High Input Impedance Voltage-Mode Biquad Filter Using VD-DIBAs

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Abstract. *This paper deals with a single-input multiple-output biquadratic filter providing three functions (low-pass, high-pass and band-pass) based on voltage differencing differential input buffered amplifier (VD-DIBA). The quality factor and pole frequency can be electronically tuned via the bias current. The proposed circuit uses two VD-DIBAs and two grounded capacitors without any external resistors, which is suitable to further develop into an integrated circuit. Moreover, the circuit possesses high input impedance, providing easy voltage-mode cascading. It is shown that the filter structure can be easily extended to multi-input filter without any additional components, providing also all-pass and band-reject properties. The PSPICE simulation results are included, verifying the key characteristics of the proposed filter. The given results agree well with the theoretical presumptions.*

Keywords

Analog filter, VD-DIBA, voltage-mode, single input-multiple output.

1. Introduction

Analog active filter is one of the standard research topics in the circuit design. It is commonly utilized block for continuous-time analog signal processing. It is generally used in many fields, such as communications, measurement, instrumentation, and control systems [1]. Especially, the filters providing several functions within a single topology, namely the universal or multifunction filter, have been receiving considerable attention. One of the most popular analog filters is a single-input, multiple-output (SIMO) topology in which various transfer functions can be realized simultaneously. The SIMO topology can be found in many applications, for example in touch-tone telephone tone decoder, in phase-locked loop FM stereo demodulator, or in crossover network as a part of the three-way high-fidelity loudspeaker [2].

The design of analog circuits using active building blocks, taking into account several various criteria such as minimum number of active elements or others, has been receiving considerable attention. Biolek et al. [3] proposed several circuit ideas of building blocks for voltage-, current- and mixed mode applications. One of them is the voltage differencing differential input buffered amplifier (VD-DIBA). This device allows applications with interesting features, especially those providing the electronic controllability. It is obvious from the literature survey that a few circuits using VD-DIBA have been hitherto published, for instance the voltage-mode first-order allpass filter [4], inductance simulator [5], and multiple-input single-output (MISO) voltage-mode biquad filter [6].

This contribution presents a SIMO voltage-mode filter with high input impedance, employing VD-DIBAs. It is suitable for fabricating as a monolithic chip or also for off-the-shelf implementation, consisting of 2 active elements and 2 grounded capacitors. The proposed filter can provide three standard functions (low-pass, high-pass and band-pass). The quality factor and pole frequency can be electronically adjusted.

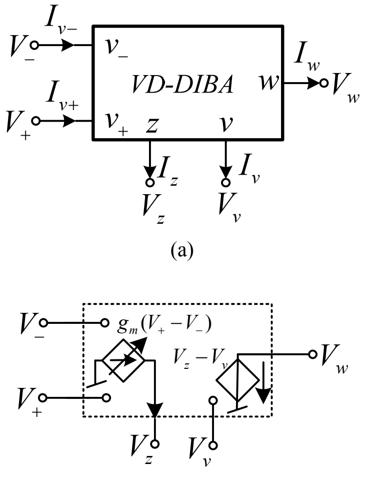
The paper is organized as follows: In Section 2, which follows this Introduction, the definition and features of the VD-DIBA are given, and the proposed filter is also presented. The non-ideal analysis is included in Section 3. The experimental results, namely SPICE simulations and measurements on a filter specimen, are illustrated in Section 4. Section 5 describes the filter extension to multi-input topology and transconductance type. The comparison with previous works is described in Section 6. Some concluding remarks are given in Section 7.

2. Theory and Principle

2.1 VD-DIBA Overview

The principle of VD-DIBA was introduced in [3]. The internal construction of VD-DIBA using commercially available ICs has been proposed in [4]. Its symbol and equivalent circuit are shown in Fig. 1(a) and (b), where V_+ and V_- are the voltage input terminals. The voltage is converted to the *z*-terminal current via a transconductance g_m, which can be tuned by the bias current. The difference of *z*- and *v*- terminal voltages is copied to the *w* terminal with the differential-input unity gain buffer. An ideal VD-DIBA has low-impedance *w* terminal and high-impedance v_+, v_-, *z*, and *v* terminals. The characteristics of VD-DIBA can be described as follows:

$$\begin{pmatrix} I_{v+} \\ I_{v-} \\ I_z \\ I_v \\ V_w \end{pmatrix} = \begin{pmatrix} 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \\ g_m & -g_m & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & -1 & 0 \end{pmatrix} \begin{pmatrix} V_+ \\ V_- \\ V_z \\ V_v \\ I_w \end{pmatrix}. \tag{1}$$



(a)

(b)

Fig. 1. VD-DIBA: (a) Symbol. (b) Equivalent circuit.

2.2 High Input Impedance Voltage-Mode Filter Using VD-DIBAs

The proposed second-order filter is illustrated in Fig. 2. It consists of two VD-DIBAs and two grounded capacitors. It is obvious that the proposed filter provides simultaneously three frequency responses (HP, LP and BP) with high input impedance property. Considering the ideal VD-DIBA, a routine analysis of the proposed filter provides the following voltage transfer functions:

$$\frac{V_{HP}}{V_{in}} = \frac{s^2}{s^2 + s\frac{g_{m2}}{C_1} + \frac{g_{m1}g_{m2}}{C_1C_2}}, \tag{2}$$

$$\frac{V_{LP}}{V_{in}} = \frac{\frac{g_{m1}g_{m2}}{C_1C_2}}{s^2 + s\frac{g_{m2}}{C_1} + \frac{g_{m1}g_{m2}}{C_1C_2}}, \tag{3}$$

and

$$\frac{V_{BP}}{V_{in}} = -\frac{s\frac{g_{m2}}{C_1}}{s^2 + s\frac{g_{m2}}{C_1} + \frac{g_{m1}g_{m2}}{C_1C_2}}. \tag{4}$$

The filter pole frequency (ω_0) and quality factor (Q) can be expressed as

$$\omega_0 = \sqrt{\frac{g_{m1}g_{m2}}{C_1C_2}}, \tag{5}$$

and

$$Q = \sqrt{\frac{C_1 g_{m1}}{C_2 g_{m2}}}. \tag{6}$$

It follows from (5) and (6) that the quality factor and pole frequency can be tuned electronically via transconductances.

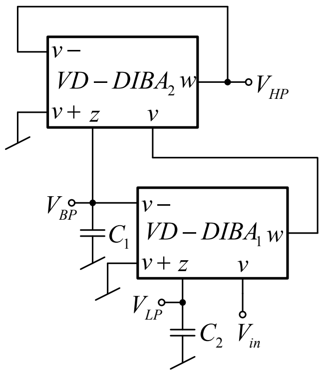


Fig. 2. Proposed voltage-mode filter.

The relative sensitivities of the proposed circuit can be found as plus or minus 0.5:

$$S_{g_{m1}}^{\omega_0} = S_{g_{m2}}^{\omega_0} = \frac{1}{2}; S_{C_1}^{\omega_0} = S_{C_2}^{\omega_0} = -\frac{1}{2}, \tag{7}$$

and

$$S_{C_1}^{Q} = S_{g_{m1}}^{Q} = \frac{1}{2}; S_{C_2}^{Q} = S_{g_{m2}}^{Q} = -\frac{1}{2}. \tag{8}$$

As a drawback, the LP and BP outputs are not of low impedance characters, thus they should be additionally buffered when applicable, or the filter topology should be modified as described in Section 5.

3. Non-ideal Case

In practice, the influences of voltage tracking errors from the unity-value gain of internal differential voltage buffer, and also the parasitic terminal impedances of VD-DIBA [4] will affect the filter performance. In this Section, these parameters will be taken into account. For non-ideal voltage buffer, its model is as follows:

$$V_w = \beta^+ V_z - \beta^- V_v. \tag{9}$$

Here β^+ and β^- are the voltage error gains from *z* and *v* terminals to *w* terminal. The influences of parasitic impedances of the *v*+, *v*- and *v* terminals of VD-DIBA No. 2 and of *v*+ and *v* terminals of VD-DIBA No. 1 are negligible because of their connection to low-impedance outputs *w*, to the input voltage source, or to ground. The most important parasitic impedances are resistive and capacitive parts affecting the *z* terminals of VD-DIBAs, acting in parallel to C_1 and C_2. Let us denote them R_{z1}, C_{z1}, and R_{z2}, C_{z2}, respectively. Taking them into account together with (9), the transfer functions will be modified to the more general forms:

$$\frac{V_{HP}}{V_{in}} = \beta_1^- \beta_2^- \frac{\left(s + \frac{1}{R_{z1}C_1'}\right)\left(s + \frac{1}{R_{z2}C_2'}\right)}{D}, \tag{10}$$

$$\frac{V_{LP}}{V_{in}} = \beta_1^- \beta_2^- \frac{\frac{g_{m1}g_{m2}}{C_1'C_2'}}{D}, \tag{11}$$

and

$$\frac{V_{BP}}{V_{in}} = -\beta_1^- \beta_2^- \frac{\frac{g_{m2}}{C_1'}\left(s + \frac{1}{R_{z2}C_2'}\right)}{D} \tag{12}$$

where $C_1' = C_1 + C_{z1}$, $C_2' = C_2 + C_{z2}$, and

$$D = s^2 + s\frac{\omega_0^*}{Q^*} + \omega_0^{*2}, \tag{13}$$

$$\omega_0^{*2} = \frac{g_{m1}g_{m2}}{C_1'C_2'}\left(\beta_1^+\beta_2^- + \frac{\beta_2^+}{g_{m1}R_{z2}} + \frac{1}{g_{m1}g_{m2}R_{z1}R_{z2}}\right), \tag{14}$$

$$Q^* = \sqrt{\frac{g_{m1}}{g_{m2}}\frac{C_1'}{C_2'}}\,\frac{\sqrt{\beta_1^+\beta_2^- + \frac{\beta_2^+}{g_{m1}R_{z2}} + \frac{1}{g_{m1}g_{m2}R_{z1}R_{z2}}}}{\beta_2^+ + \frac{1}{g_{m2}R_{z1}} + \frac{C_1'}{C_2'}\frac{1}{g_{m1}g_{m2}R_{z1}R_{z2}}}. \tag{15}$$

It should be mentioned that the stray/parasitic *z*-terminal capacitances are absorbed by the external grounded capacitors as they appear in shunt with them. However, the parasitic resistances R_{z1} and R_{z2} not only affect the ω_0 and Q by they also add parasitic zeros to the HP and BP transfer functions. The product $\beta_1^-\beta_2^-$ of the voltage buffer gains affects the gain of all the filter sections. As a result, the effect of the finite low-frequency attenuation of BP and HP sections appears [7]. It can be described as follows:

$$\left.\frac{V_{in}}{V_{BP}}\right|_{f=0} = -\frac{\beta_2^+}{\beta_1^-\beta_2^-}\left(1 + \frac{1}{\beta_2^+ g_{m2}R_{z1}} + \frac{\beta_1^+\beta_2^-}{\beta_2^+}g_{m1}R_{z2}\right), \tag{16}$$

$$\left.\frac{V_{in}}{V_{HP}}\right|_{f=0} = \frac{1}{\beta_1^-\beta_2^-}\left(1 + \beta_2^+ g_{m2}R_{z1} + \beta_1^+\beta_2^- g_{m1}R_{z1}g_{m2}R_{z2}\right)\cdot \tag{17}$$

Note that these undesirable finite attenuations strongly depend on the g_mR_z product. Consider unity gains of the voltage buffers for the simplicity. Let us denote $g_mR_z=a$. Then (16) and (17) can be simplified to the forms

$$\left.\frac{V_{in}}{V_{BP}}\right|_{f=0} = -\left(1 + a + \frac{1}{a}\right), \tag{18}$$

$$\left.\frac{V_{in}}{V_{HP}}\right|_{f=0} = 1 + a + a^2\cdot \tag{19}$$

Then one can see that $a = g_mR_z$ products of 10^1, 10^2, 10^3, and 10^4 result in the attenuations (18) of 20.9, 40.1, 60, 80 dB for BP output, and in the attenuations (19) of 40.9, 80.1, 120, 160 dB for HP output. Two rules of thumb can be applied: 1) The BP low-frequency attenuation can be increased by 20 dB via increasing the g_mR_z product ten times. 2) The HP low-frequency attenuation is twice the size.

Similarly, Equations (14) and (15) for pole frequency and quality factor can be simplified as follows:

$$\frac{\omega_0^*}{\omega_0} = \sqrt{\frac{C_1C_2}{C_1'C_2'}}\sqrt{1 + \frac{1}{a} + \frac{1}{a^2}}, \tag{20}$$

$$\frac{Q^*}{Q} = \sqrt{\frac{C_1'}{C_1}\frac{C_2}{C_2'}}\,\frac{\sqrt{1 + \frac{1}{a} + \frac{1}{a^2}}}{1 + \frac{1}{a} + \frac{C_1'}{C_2'}\frac{1}{a^2}}. \tag{21}$$

It follows from (20) and (21) that high values of *a*, which are necessary for suppressing parasitic low-frequency gains, ensure that the pole frequency and quality factor are not affected by the finite parasitic resistances R_z.

Note that the analysis of non-ideal case should include the current limits I_{max} of the internal g_m-stages of VD-DIBAs. Since these OTAs operate to grounding capacitors connected to *z* terminals of VD-DIBAs, the maximum voltages V_{max} at the filter outputs are limited by the values

$$V_{\max} = \frac{I_{\max}}{\omega C}. \tag{22}$$

In spite of the simplicity of (22), it describes well the potential limitations of the dynamic range of the filter due to nonlinear issues: The appropriate dynamic range can be ensured more problematically for high-frequency biquad, employing g_m stages with insufficient current-driving capability, especially with high working capacitances. However, the above parameters can be typical for non-on-chip filter prototyping from commercial ICs.

4. Experimental Results

The proposed universal filter in Fig. 2 was designed with the following parameters: $C_1 = C_2 = 10$ nF, $g_{m1} = g_{m2} = 10$ mS. The corresponding theoretical values of the pole frequency and quality factor are $f_0 = 159$ kHz and $Q = 1$. The relatively high capacitances were selected in order to provide reasonably high $g_m R_z$ product as explained below.

The VD-DIBA was implemented from commercial ICs as shown in Fig. 3. It consists of two basic blocks: the operational transconductance amplifier-OTA (MAX435) [8] as input stage and the differential-input buffer (AD8130) [9] as output stage. The transconductance gain (g_m) can be adjusted by external resistor R_g ($g_m = 4/R_g$) of the MAX435. The DC power supply voltages are ±5 V.

As obvious from Fig. 3, R_g was finally selected as 390 Ω. The corresponding values of g_m and f_0 are 10.26 mS and 163 kHz, respectively. The resistor R_{set} in Fig. 3 was designed according to the datasheet [8], providing the upper limit of 10 mA of the OTA current.

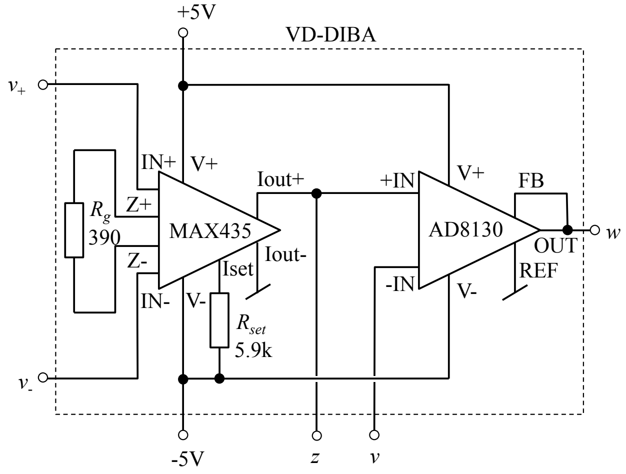


Fig. 3. VD-DIBA implementation by ICs MAX435 and AD8130.

In addition to excellent parameters of MAX435 (275 MHz bandwidth, 850 V/μs slew rate, 18 ns settling time, linear I/V characteristic), it provides rather low resistances R_z of the current outputs. The measured values are only 5 kΩ. It gives, together with the above value of g_m, the product $g_m R_z = 51.3$. According to (16) and (17), the estimated parasitic low-frequency attenuations at BP and HP outputs will be 34.4 dB and 68.6 dB, respectively. As shown below, these values correspond well with SPICE simulations and measurements. If higher values are requested, one should decrease R_z and increase capacitances accordingly, this way preserving the required pole frequency. As results from (20) and (21), $g_m R_z = 51.3$ causes negligible increase of pole frequency and decrease of the quality factor (below one per cent).

Before manufacturing the prototype, the designed filter was simulated in PSpice. The VD-DIBA was modeled via SPICE models of MAX435 [10] and AD8130 [11]. Since the model from [10] does not consider the output resistance R_z of the current outputs of MAX435, it was modeled by auxiliary resistor with $R_z = 5$ kΩ. The simulated frequency responses, compared with the characteristics for ideal case ($R_z \to \infty$) and with the characteristics measured via the network analyzer Agilent E4061B are shown in Fig. 4. Note that the measured values were imported in PSpice by look-up-table-controlled sources. The extrapolated low-frequency attenuations are 33.8 dB at BP output and 67.1 dB at HP output. It is in a good agreement with the above mentioned values from the error analysis. The measured pole frequency deviates from the theoretical value by less than 7% due to tolerance of passive components.

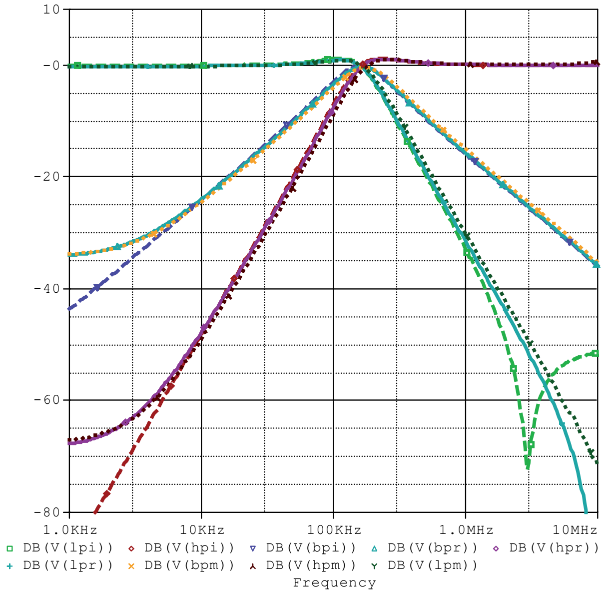


Fig. 4. Frequency responses of the designed filter; lpi, bpi, hpi: SPICE simulation, $R_z \to \infty$; lpr, bpr, hpr: SPICE simulation, $R_z = 5$ kΩ; lpm, bpm, hpm: measured.

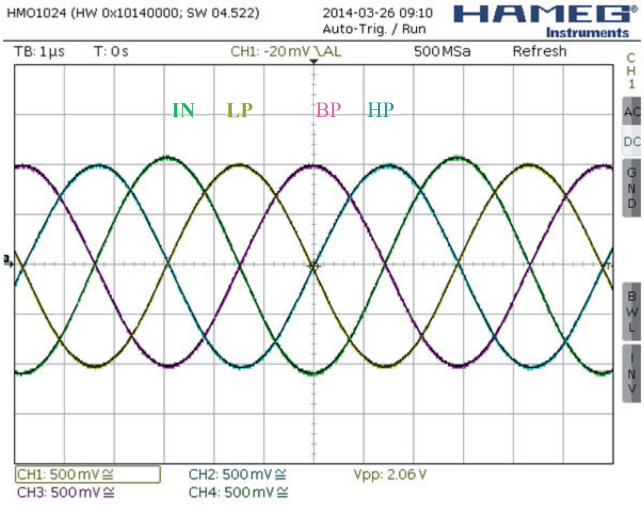


Fig. 5. Large-signal steady-state operation of the manufactured filter for sinusoidal 1.07 V/172 kHz excitation.

In addition to the above small-signal measurements, the manufactured filter was excited by sinusoidal signal in order to test the filter stability and signal limits due to nonlinear distortion. For large-signal operation, the pole frequency tends to be slightly increased due to nonlinear effects. Figure 5 shows the measured waveforms for sinusoidal 1.07 V/172 kHz signal. The THD measured are 0.76 %, 0.5 %, and 0.53 % for HP, BP, and LP outputs, respectively. The magnitudes above ca 1 V cause high increase of the nonlinear distortion due to current limitations of the g_m stages of VD-DIBAs. Such low dynamic range is caused by high capacitances used in the filter. For the upper current limit 10 mA for MAX435, $C = 10$ nF and frequency 172 kHz, the upper limit of the voltage according to (22) is 0.925 V. It is in very good agreement with the measurements.

5. Biquad Generalization

The filter from Fig. 2 can be generalized as shown in Fig. 6, considering five voltage inputs V_{i1} to V_{i5} and two current outputs I_{o1} and I_{o2}, the latter being added via a "z-copy" technique [3]. The types of filter sections, corresponding to input-output pairs, are summarized in Tab. 1. The highlighted three items on the first line denoted "V_{i1}" describe the features of the original filter from Fig. 2.

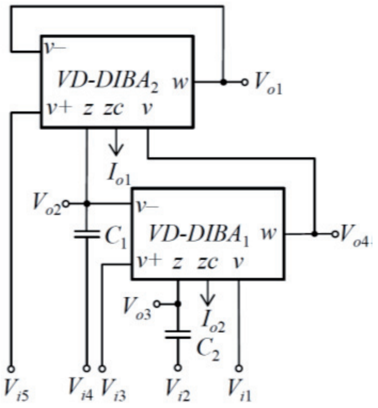


Fig. 6. Multi-input multi-output generalization of filter from Fig. 2.

	V_{o1}	V_{o2}	V_{o3}	V_{o4}	I_{o1}	I_{o2}
V_{i1}	*HP*	*-BP*	*LP*		$-HP^{(2)}$	$-BP^{(4)}$
V_{i2}	*-HP*	*BP*			$HP^{(2)}$	$-BP^{(4)}$
V_{i3}	$-BP^{(1)}$	*LP*			$BP^{(3)}$	
V_{i4}		*HP*	$-BP^{(1)}$	$-BP^{(1)}$		$-HP^{(4)}$
V_{i5}		*BP*	*-LP*	*-LP*	$HP^{(2)}$	$-BP^{(4)}$
$V_{i1}=V_{i3}=V_{i4}$		*AP*				
$V_{i3}=V_{i4}$		*BR*				

(1) BP gain is $g_{m2}C_1/(g_{m1}C_2)$, (2) HP gain is g_{m1}, (3) BP gain is $g_{m2}C_1/C_2$, (4) BP (HP) gain is g_{m2}; otherwise, the gains are equal to one.

Tab. 1. Low-pass (LP), band-pass (BP), high-pass (HP), all-pass (AP) and band-reject (BR) sections of multi-input multi-output filter in Fig. 6.

Note that particularly the column "V_{o2}" represents a promising extension of the biquad features: utilizing the output V_{o2}, all basic filter types can be implemented via a proper selection of the inputs, including allpass and band-reject sections (by interconnecting three or two inputs).

The additional current outputs of the internal OTAs of VD-DIBA No. 1 and 2 can easily serve as current outputs of BP and HP sections, enabling economical extension of the filter operation to the transconductance mode.

In the necessity of providing buffered, thus true voltage-mode HP, BP or LP outputs, one can use V_{o1} or V_{o4} terminals. For the operations when the input V_{i1} is not used, the feedback loop to the *v* terminal of VD-DIBA No. 2 should be led not from *w* but from *z* terminal of VD-DIBA No. 1. Since the output buffer is no longer included in the feedback loop, the filter stability and high-frequency behavior will be improved.

6. Comparison with Previous SIMO Voltage-Mode Filters

Literature survey shows that a lot of papers dealing with SIMO voltage-mode filter using various active building blocks have been published [12-30]. Considering the kinds of active elements, the filters in the above references employ: current feedback amplifier (CFA) [12], current conveyor (CCII) [13], [14], four terminal floating nullor (FTFN) and operational transconductance amplifier (OTA) [15], differential voltage current conveyor (DVCC) [16-19], differential different current conveyor (DDCC) [20-22], DDCC and OTA [23], OTA [24-26], differential difference current conveyor transconductance amplifier (DDCCTA) [27], [28], fully differential current conveyor (FDCCII) [29-31], DDCC and current controlled current conveyor (CCCII) [32].

The proposed circuit in Fig. 2 is compared with several SIMO voltage-mode filters from [12-32]. The results are shown in Tab. 2. It can be seen that it matches all the criteria in the best way among all other filters.

In addition to the above SIMO filters, the three-input single-output voltage-mode biquad utilizing one VDIBA (voltage differencing inverting buffered amplifier) [33], two capacitors, and one resistor has been published in [34] and also in [35]. Note that VDIBA differs from VD-DIBA by voltage inverter which replaces the differential-input buffer in VD-DIBA. The filter from [34], [35] pays a tax for employing only one active element: Electronic control is limited to one parameter, namely the transconductance of the VD-DIBA, thus the controlling range is smaller in comparison to (5), without any possibility not to disturb Q with tuning f_0. Since the single output is not of low-impedance nature, all the implemented filter types require additional voltage buffering.

7. Conclusions

The voltage-mode biquad filter has been presented in this contribution. The advantages of the proposed circuit are that: (i) it performs low-pass, high-pass, and band-pass, functions from the same simple circuit configuration; (ii) the quality factor and the pole frequency can be electronically controlled; (iii) the filter has high input impedance; (iv) the circuit uses only two VD-DIBAs, two grounded capacitors and no resistors, which is attractive for its IC implementation; (v) the functionality of the filter can be easily extended for providing all-pass and band-reject sec-

Ref	Active elements	No. of active elements	No. of R+C	Electronic control	Grounded capacitors only	High input impedance
[12]	CFA	5	5+2	No	Yes	Yes
[13]	CCII	3(cir.1), 4(cir.2)	6+2(cir.1), 7+2(cir.2)	No	Yes	No
[14]	CCII	4(cir.1&cir.2), 3(cir.3), 2(cir.4)	5+2	No	Yes	No
[15]	FTFN & OTA	2 & 2	4+2	Yes	Yes	Yes
[16]	DVCC	3	4+2	No	Yes	Yes
[17]	DVCC	3	3+2	No	Yes	Yes
[18]	DVCC	2	3+2	No	Yes	No
[19]	DVCC	1	2+3	No	No	Yes
[20]	DDCC	2	3+2	No	Yes	No
[21]	DDCC	2	3+2	No	Yes	No
[22]	DDCC	1	3+2	No	Yes	No
[23]	DDCC & OTA	1 & 2	0+2	Yes	Yes	Yes
[24]	OTA	5	0+2	Yes	Yes	Yes
[25]	OTA	8	0+2	Yes	Yes	Yes
[26]	OTA	4	0+2	Yes	Yes	Yes
[27]	DDCCTA	2	2+2	Yes	Yes	Yes
[28]	DDCCTA	3	0+2	Yes	Yes	Yes
[29]	FDCCII	2	2+2	No	Yes	Yes
[30]	FDCCII	1	3+2	No	Yes	No
[31]	FDCCII	1	2+2	No	Yes	Yes
[32]	DDCC & CCCII	1+1	1+2	Yes	Yes	Yes
Proposed filter	VD-DIBA	2	0+2	Yes	Yes	Yes

Tab. 2. Comparison of various SIMO voltage-mode filters.

tions via selecting various types of voltage inputs; (vi) the filter topology provides a possibility of its flexible modification and development, depending on the user's requirements, for example towards the transconductance mode of the operation.

The error analysis reveals that parasitic low-frequency gains of BP and HP sections can be suppressed via selecting the $g_m R_z$ product as high as possible. As results from the experiments described in Section 4, VD-DIBA should be implemented with R_z high enough. Otherwise, g_m must be designed too high, which results in large working capacitances. Then the corresponding low impedance level is a source of several troubles, especially low dynamic range of the voltage signals. For IC implementation, designing VD-DIBA with extra-high *z*-terminal impedance is thus a prerequisite for constructing high-performance biquads.

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References

[1] SEDRA, A. S., SMITH, K. C. *Microelectronic Circuits*. 3rd ed. Florida: Holt, Rinehart and Winston, 1991.

[2] IBRAHIM, M. A., MINAEI, S., KUNTMAN, H. A 22.5MHz current-mode KHN-biquad using differential voltage current conveyor and grounded passive elements. *International Journal of Electronics and Communications (AEÜ)*, 2005, vol. 59, no. 5, p. 311–318.

[3] BIOLEK, D., SENANI, R., BIOLKOVÁ, V., KOLKA, Z. Active elements for analog signal processing, classification, review and new proposals. *Radioengineering*, 2008, vol. 17, no. 4, p. 15–32.

[4] BIOLEK, D., BIOLKOVÁ, V. First-order voltage-mode all-pass filter employing one active element and one grounded capacitor. *Analog Integrated Circuits and Signal Processing*, 2009, vol. 65, no. 1, p. 123–129.

[5] PRASAD, D., BHASKAR, D. R., PUSHKAR, K. L. Realization of new electronically controllable grounded and floating simulated inductance circuits using voltage differencing differential input

buffered amplifiers. *Active and Passive Electronic Components*, 2011, vol. 2011, Article ID: 101432.

[6] PUSHKAR, K. L., BHASKAR, D. R., PRASAD, D. Voltage-mode universal biquad filter employing single voltage differencing differential input buffered amplifier. *Circuits and Systems,* 2013, vol. 4, p. 47–51.

[7] BIOLEK, D., BAJER, J., BIOLKOVÁ, V., KOLKA, Z., KUBÍČEK, M. Z Copy - Controlled Gain - Current Differencing Buffered Amplifier and its applications. *Int. Journal of Circuit Theory and Applications.* 2011, vol. 39, no. 3, p. 257–274.

[8] MAX435/MAX436 Wideband Transconductance Amplifiers, MAXIM, 19-0042; Rev. 1; 4/93.

[9] AD8129/AD8130 Low Cost 270 MHz Differential Receiver Amplifiers, Analog Devices, 2005. Available at: www.analog.com.

[10] MAX435 Family Macromodels, http://www.maximintegrated.com/design/tools/modeling-simulation/spice/operational-amplifiers/macro/MAX435.FAM

[11] AD8130 SPICE Macro-Model http://www.analog.com/en/specialty-amplifiers/differential-amplifiers/ad8130/products/mod-spice-models/resources.html

[12] ABUELMA'ATTI, M. T., AL-ZAHER, H. A. New universal filter with one input and five outputs using current-feedback amplifiers. *Analog Integrated Circuits and Signal Processing,* 1998, vol. 16, p. 239–244.

[13] HORNG, J. W., HOU, C., L., CHANG, C. M., CHUNG, W. Y., WEI, H. Y. Voltage-mode universal biquadratic filter with one input and five outputs using MOCCIIs. *Computers & Electrical Engineering*, 2005, vol. 31, p. 190–202.

[14] HORNG, J. W., HOU, C., L., CHANG, C. M., CHUNG, W. Y. Voltage-mode universal biquadratic filter with one input and five outputs. *Analog Integrated Circuits and Signal Processing,* 2006, vol. 47, p. 73–83.

[15] KUMAR, K., PAL, K. Voltage-mode universal biquadratic filter using FTFN and OTA. *Journal of Electrical and Electronics Engineering*, 2009, vol. 9, no. 2, p. 1083–1087.

[16] HORNG, J. W., HOU, C. L., CHANG, C. M., CHOU, H. P., LIN, C. T. High input impedance voltage-mode universal biquadratic filter with one input and five outputs using current conveyors. *Circuits System Signal and Processing*, 2006, vol. 25, no. 6, p. 767–777.

[17] MINAEI, S., YUCE, E. All-grounded passive elements voltage-mode DVCC-based universal filter. *Circuits System Signal and Processing*, 2010, vol. 29, p. 295–309.

[18] HORNG, J. W. Lossless inductance simulation and voltage-mode universal biquadratic filter with one input and five outputs using DVCCs. *Analog Integrated Circuits and Signal Processing*, 2010, vol. 62, p. 407–413.

[19] HORNG, J. W. Voltage-mode multifunction biquadratic filter employing single DVCC. *International Journal of Electronics*, 2012, vol. 99, no. 2, p. 153–162.

[20] CHEN, H. P. Universal voltage-mode filter using only plus-type DDCCs. *Analog Integrated Circuits and Signal Processing*, 2007, vol. 50, no. 2, p. 137–139.

[21] CHIU, W. Y., HORNG, J. W. Voltage-mode biquadratic filters with one input and five outputs using DDCCs. *Indian Journal of Engineering and Materials Sciences,* 2011, vol. 18, p. 97–101.

[22] CHIU, W. Y., HORNG, J. W. Voltage-mode highpass, bandpass, lowpass and notch biquadratic filters using single DDCC. *Radioengineering*, 2012, vol. 21, no. 1, p. 297–303.

[23] LEE, W. T., LIAO, Y. Z. New voltage-mode high-pass, band-pass and low-pass filter using DDCC and OTAs. *International Journal of Electronics and Communications (AEÜ)*, 2008, vol. 62, no. 9, p. 701–704.

[24] HORNG, J. W. Voltage-mode universal biquadratic filter with one input and five outputs using OTAs. *International Journal of Electronics*, 2002, vol. 89, p. 729–737.

[25] KUMNGERN, M., SUWANJAN, P., DEJHAN, K. Electronically tunable voltage-mode universal filter with single-input five-output using simple OTAs. *International Journal of Electronics*, 2013, vol. 100, no. 8, p. 1118–1133.

[26] KUMNGERN, M., DEJHAN, K. Voltage-mode low-pass, high-pass, band-pass biquad filter using simple CMOS OTAs. In *Proceedings of the IEEE International Instrumentation and Measurement Technology Conference*. 2009, p. 924–927.

[27] CHANNUMSIN, O., PUKKALANUN, T., TANGSRIRAT, W. Voltage-mode universal filter with one input and five outputs using DDCCTAs and all-grounded passive components. *Microelectronics Journal*, 2012, vol. 43, no. 8, p. 555–561.

[28] TANGSRIRAT, W., CHANNUMSIN, O., PUKKALANUN, T. Resistorless realization of electronically tunable voltage-mode SIFO-type universal filter. *Microelectronics Journal*, 2012, vol. 43, no. 8, p. 555–561.

[29] CHEN, H. P. Voltage-mode FDCCII-based universal filters. *International Journal of Electronics and Communications (AEÜ),* 2008, vol. 62, no. 4, p. 320–323.

[30] LEE, C. N., CHANG, C. M. Single FDCCII-based mixed-mode biquad filter with eight outputs. *International Journal of Electronics and Communications (AEÜ)*, 2009, vol. 63, p. 736 to 742.

[31] MAHESHWARI, S., MOHAN, J., CHAUHAN, D. S. Novel cascadable all-pass/notch filters using a single FDCCII and grounded capacitors. *Circuits, Systems, and Signal Processing*, 2011, vol. 30, no. 3, p. 643–654.

[32] MANEEWAN, S., SREEWIROTE, B., JAIKLA, W. Electronically tunable voltage-mode universal filter using DDCC and CCCII. In *Proceedings of the International Conference on Circuits, System and Simulation*. 2011, p. 322–326.

[33] HERENCSÁR, N., KOTON, J., MINAEI, S., YUCE, E., VRBA, K. Novel resistorless dual-output VM all-pass filter employing VDIBA. In *Proceedings of the 7th International Conference on Electrical and Electronics Engineering–ELECO 2011*. Bursa (Turkey), 2011, p. 72–74.

[34] HERENCSÁR, N., CICEKOGLU, O., ŠOTNER, R., KOTON, J., VRBA, K. New resistorless tunable voltage-mode universal filter using single VDIBA. *Analog Integrated Circuits and Signal Processing*, 2013, vol. 76, p. 251–260.

[35] PUSHKAR, K. L., BHASKAR, D. R., PRASAD, D. Voltage-mode new universal biquad filter configuration using a single VDIBA. *Circuits Systems and Signal Processing*, 2014, vol. 33, p. 275–285.

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