All-Pass Filter Employing Fully Balanced Voltage Differencing Buffered Amplifier

Dalibor Biolek
Dept. of EE & Dept. of Microelectronics
FEEC, Brno Univ. of Technology&FVT, Univ. of Defence
Brno, Czech Republic
dalibor.biolek@unob.cz

Viera Biolkova and Zdenek Kolka
Dept. of Radioelectronics
FEEC, Brno Univ. of Technology
Brno, Czech Republic
biolkova@feec.vutbr.cz

***Abstract*—A new circuit topology of first-order all-pass filter based on FB-VDBA (Fully Balanced Voltage Differencing Buffered Amplifier) is proposed. The filter consists of one active element, one grounded capacitor, and one resistor with the resistance $R=1/g_m$, where g_m is the FB-VCBA transconductance. The filter operates in the voltage-mode, providing high-impedance input and low-impedance output. It is assembled from commercial integrated circuits, and the frequency responses measured are included.**

Keywords-Voltage mode; all-pass filter; FB-VCBA

I. INTRODUCTION

The first-order all-pass filter represents an important building block with a broad application potential in analog signal processing, oscillator circuits, communication systems and in instrumentation electronics. A number of circuits have been proposed till this time, utilizing assorted active elements, from conventional voltage-feedback operational amplifiers (OpAmps) [1], through different types of current conveyor [2-5], Four Terminal Floating Nullors (FTFN) [6, 7], Current Feedback OpAmps [8], Operational Transconductance Amplifiers (OTAs) [9], to elements employing the Current Differencing Unit such as OTRA [10], CDBA [11-13], and CDTA [14-16]. In [17], the all-pass section is designed by means of OTA, differential voltage unity-gain amplifier, and active voltage divider. The main reasons for the all-pass filter design with assorted types of active elements are the necessity of utilizing voltage-, current-, and mixed-mode circuits, and also the demand for simple circuit implementation with a minimum number of active and passive components, low sensitivities to parameter variations, and the absence of matching conditions among the component parameters which would determine the proper filter operation. The input and output impedances should be ideally equal to zero or infinity, depending on the type of input and output ("0/∞" impedance for short). The use of only grounded capacitors and a minimum number of resistors is advantageous for implementing the all-pass filter as an integrated circuit (IC). The above common requirements are frequently extended by the need for electronic control of natural frequency.

Detailed analysis of the circuits from the above papers confirms how difficult it is to fulfill all these requirements simultaneously. For example, only the filters from [5, 6, 17] satisfy the requirement for "0/∞" input impedance. Analogous requirement on the output impedance is fulfilled by a number of circuits, but only two of them [5, 17] meet both the requirements simultaneously. Natural frequency can be controlled electronically in all-pass filters from [4, 7, 9, 12, 13, 15-17]. However, only five filters do not use floating capacitors and do not suffer from matching condition constraints [3-5, 7, 16], and only one of them [5] has "0/∞" input and output impedances. Unfortunately, the filter from [5] cannot be electronically controlled.

The first-order all-pass filter described in this paper extends the collection of all-pass sections with "0/∞" input and output impedances. Note that only two from the above circuits ([5], and [17]) belong to this group, with the pairs ∞/∞ and ∞/0 of their input/output impedances, respectively. The all-pass section from [5] contains two DDCC (Differential Difference Current Conveyor), one grounded capacitor and one grounded resistor. As already noted, the filter from [17] consists of one grounded capacitor, two active elements, and also one voltage divider, employing two transistors while our solution uses one grounded capacitor, one floating resistor, and one active element, FB-VDBA (Fully Balanced Voltage Differencing Buffered Amplifier) [18], which is a generalized version of VDDOBA (Voltage Differencing Differential Output Buffered Amplifier) [19]. The FB-VDBA is of a simple design, which is advantageous in comparison with circuits from [5, 17]. A matching condition, which is defined in Section III, must be fulfilled. However, it can be easily accomplished via electronic control of the internal transconductance of FB-VDBA.

The paper has the following structure: The FB-VDBA and its possible implementations from commercially available integrated circuits, namely Operational Transconductance Amplifiers or diamond transistors, are briefly introduced. Then a new circuit topology of all-pass filter based on FB-VDBA is described, and its transfer function is shown. A non-ideal analysis follows. The final Section summarizes the results of measurements on the filter specimen.

II. FULLY BALANCED VDBA

The schematic symbol and behavioral model of the FB-VDBA are shown in Figs. 1 (a) and (b). The model can be described by the following set of equations:

$$\begin{pmatrix} I_{z+} \\ I_{z-} \\ V_{w+} \\ V_{w-} \end{pmatrix} = \begin{pmatrix} g_m & -g_m & 0 & 0 \\ -g_m & g_m & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} V_+ \\ V_- \\ V_{z+} \\ V_{z-} \end{pmatrix}. \quad (1)$$

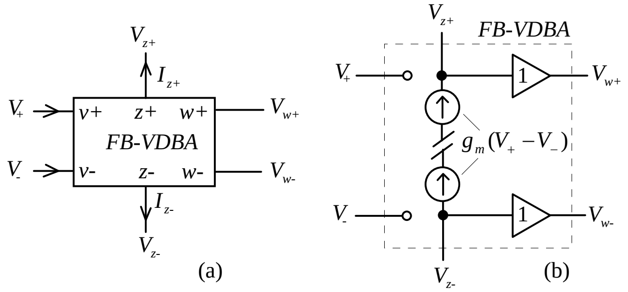

Figure 1. (a) Schematic symbol, (b) behavioral model of FB-VDBA.

It follows from the above that FB-VDBA can be compiled from a Differential Input-Differential Output (DIDO) OTA and a pair of voltage buffers according to Fig. 2 (a). Since the commercial DIDO-OTA, MAX 435, is already an obsolete element, Fig. 2 (b) shows another FB-VDBA implementation from two ICs, namely OPA 860 [20]. OPA860 contains the so-called diamond transistor and the fast voltage buffer. The diamond transistor with its terminals E (emitter), B (base) and C (collector) acts as a current-controlled current conveyor CC-CCII+ with X, Y, and Z terminals, with resistance $R_x = 1/g_{mT}$ of the x terminal, where g_{mT} is the diamond transistor transconductance, electronically controllable via a bias current. The diamond transistor can also be regarded as an OTA, because the current flowing from the collector and also from the emitter is proportional to the transconductance and to the base-emitter voltage. In order to increase the linearity of collector current versus input voltage, a degenerating resistor $R_g >> R_x$ is added in series to the emitter. Then the total transconductance decreases to the approximate value $1/R_g$. The pair of transistors $T+$ and $T-$ in Fig. 2 (b) is connected such that it forms a differential-input differential-output OTA. A sufficiently high value of R_g ensures a high input resistance of the amplifier and also minimizes the influence of the voltage offset of transistors on the offsets of currents I_z. In the extreme case, R_g can be replaced by a short circuit. Then the OTA transconductance will be determined only by the internal transconductances of diamond transistors, thus enabling its electronic control. However, we will lose all the benefits resulting from the effects of the negative feedback caused by the degenerating resistor.

III. ALL-PASS FILTER EMPLOYING FB-VDBA

Fig. 3 shows an FB-VDBA circuit with the following transfer function:

$$\frac{V_{out}}{V_{in}} = \frac{1 - sCR}{1 + sC/g_m}. \quad (2)$$

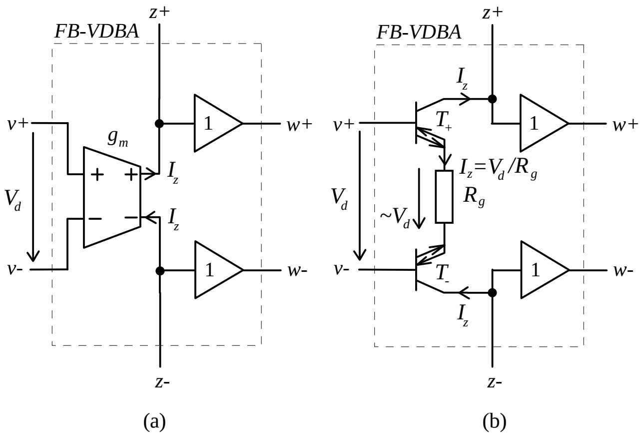

Figure 2. FB-VDBA implementation via (a) OTA MAX435 and two voltage buffers, (b) two OPA860.

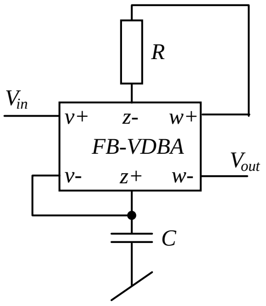

Figure 3. All-pass filter with transfer function (2).

Note that (2) represents the transfer function of the inverting-type all-pass filter when condition (3) is fulfilled:

$$g_m = \frac{1}{R}. \quad (3)$$

The filter natural frequency is then as follows:

$$\omega_0 = \frac{1}{RC}. \quad (4)$$

Note also that this filter provides ideally an infinite input and a zero output impedance, thus it belongs to the group of “0/∞” all-pass filters working in the voltage mode.

IV. NON-IDEAL EFFECTS

The frequency response of the all-pass section is influenced by the real parameters of the FB-VDBA. An analysis shows the dominant effect of the following parameters:

1) Input resistances/capacitances of terminals $v+/v-$, i.e. R_{v+}, C_{v+}, R_{v-}, C_{v-}.

2) Output resistances/capacitances of terminals $z+/z-$, i.e. R_{z+}, C_{z+}, R_{z-}, C_{z-}.

3) Output resistances of terminals $w+$, $w-$, i.e. R_{w+}, R_{w-}.

4) Transconductances $g_{m+}=I_{z+}/(V_+-V_-)$ and $g_{m-}=I_{z-}/(V_+-V_-)$ and their frequency dependence may not be identical.

5) Deviations of voltage gains b_{w+} and b_{w-} of internal voltage buffers from unity values and frequency dependence of these gains.

The first three groups of effects are indicated in Fig. 4 as low-signal parasitic impedances, where

$$R_p = R_{v-} \text{ II } R_{z+},\ C_p = C_{v-} + C_{z+}. \quad (5)$$

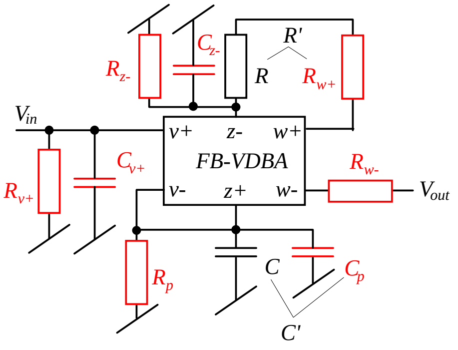

Figure 4. Parasitic impedances of FB-VDBA affecting filter operation.

Note from Fig. 4 that resistors R_{w+} and R are in series and that capacitors C_p and C are in parallel, and therefore the R and C parameters, affecting the zero- and pole-frequencies of transfer function (2) are increased to the values

$$R' = R+R_{w+},\ C' = C+C_p. \quad (6)$$

Assuming that the filter is driven by a low-impedance voltage source and that the loading impedance is much higher than the buffer output resistance R_{w-}, the influence of parameters R_{v+}, C_{v+}, and R_{w-} on the filter frequency response can be neglected. Considering the remaining real factors 1) to 5), the transfer function analysis leads to the following result:

$$\frac{V_{out}}{V_{in}} = \frac{K_0}{1+s\dfrac{C_{z-}}{G'+G_{z-}}}\,\frac{1-s\dfrac{C'}{G_{num}}}{1+s\dfrac{C'}{G_{den}}}, \quad (7)$$

where

$$K_0 = b_{w-}\frac{g_{m-}}{G_p+g_{m+}}\,\frac{b_{w+}G'\dfrac{g_{m+}}{g_{m-}}-G_p}{G'+G_{z-}}, \quad (8)$$

$$G_{num} = b_{w+}G'\frac{g_{m+}}{g_{m-}} - G_p,\ G_{den} = g_{m+} + G_p. \quad (9)$$

The conventional notation $G = 1/R$ for conductances is used here.

Transfer function (7) is derived on the assumption of frequency independent transconductances and voltage gains of buffers, assuming that the cutoff frequencies of the appropriate frequency responses are located above the frequency range of the all-pass filter.

It follows from (7) that the parasitic capacitance C_{z-} is the cause of an additional pole of the transfer function, and that other real factors, appearing on right-hand sides of Eqs. (8) and (9), affect the filter DC transfer and the original transfer zero $+\omega_0$ and pole $-\omega_0$.

The influence of the additional pole can be eliminated by satisfying condition (10):

$$RC >> R_{z-}C_{z-}. \quad (10)$$

The equality of absolute values of transfer zero and pole, which provides for frequency independent gain, leads to the equality

$$b_{w+}\frac{g_{m+}}{g_{m-}} = R'g_{m+} + 2\frac{R'}{R_p}, \quad (11)$$

which yields condition (3) when neglecting all the parasitic parameters. Under the influence of real parameters, condition (11) can be satisfied via adjusting g_m or R.

An analysis of (8) shows that when buffer gains are not higher than 1, the low-frequency transfer of the filter will be always less than 1. This parasitic attenuation is the more pronounced, the closer resistance R approaches the value of R_p. That is why the following design condition should be satisfied:

$$R << R_p. \quad (12)$$

V. EXPERIMENTAL VERIFICATION

For the purposes of experimental verification of the proposed circuit, an all-pass filter with natural frequency f_0 = 100 kHz was designed and manufactured on the basis of two OPA860 according to Figs 2(b) and 3. OPA860 was supplied with symmetrical voltages of ±5V. Based on the recommendation in [20], auxiliary 100 Ω resistors were included in series with transistor bases, and internal transconductances g_{mT} of both diamond transistors were set via auxiliary resistors R_{adj1} and R_{adj2}. The values R = 100 Ω and C = 15 nF were used in the implementation, and the corresponding theoretical value of the natural frequency was 106 kHz. The R_g resistance, having a share in defining the transconductance of FB-VDBA, was designed to be 75 Ω, and condition (3) was additionally set by internal transconductances of diamond transistors in order to equalize the amplitude frequency response. The frequency responses measured are compared with theoretical curves, obtained by PSpice analysis of ideal transfer function (2), in Fig. 5. The low-frequency attenuation of ca 0.11 dB is caused by real factors which are described by Eq. (8), and it is quite low due to the relatively low value of R and also to respecting condition (12). The experimental results correspond well with the design intentions. The imperfections in the frequency region from ca 10 MHz are caused by the frequency limitations of diamond transistors and buffers, and the parasitic pole in transfer function (7) also takes the effect here.

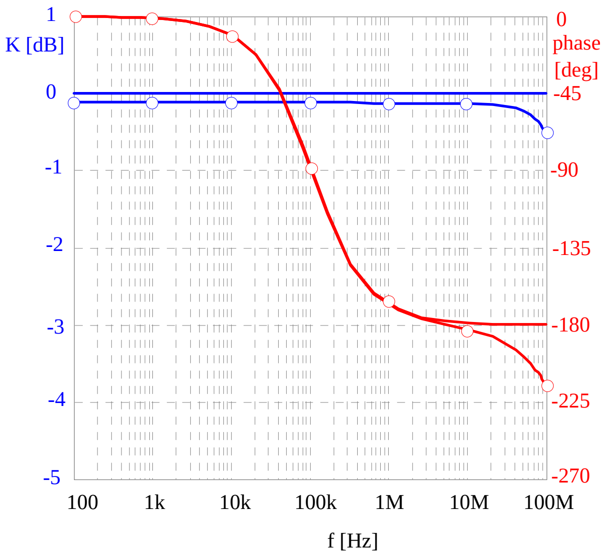

Figure 5. Frequency responses of all-pass filter from Fig. 3, ___ theoretical, -○- measured.

VI. CONCLUSIONS

The first-order all-pass section, described in this paper, employs a single active element FB-VDBA and two passive components, namely grounded capacitor *C* and floating resistor *R*. This filter operates in the voltage-mode and enables easy cascading of the building blocks due to its high-impedance input and low-impedance output. The matching condition $g_m R=1$, where g_m is the internal transconductance of FB-VDBA, can be used for precise trimming of the frequency response via electronic control of g_m. It is also shown that FB-VDBA can be easily made up from two commercial integrated circuits. Measurements on the manufactured filter confirm its proper operation in the frequency range up to tens of MHz.

ACKNOWLEDGMENTS

Research described in the paper was supported by the Czech Grant Agency under grants 102/08/0784, 102/10/1665, and 102/09/1628, by the research programmes of BUT No. MSM0021630503/513 and UD Brno No. MO FVT0000403, by the European Community’s Seventh Framework Programme under agreement No. 230126, and by the ENIAC European Programme E3CAR.

REFERENCES

[1] A. M. Soliman, “Realization of operational amplifier all-pass networks, “ Electronics Letters, vol. 9, no pp 67-68, 1973.

[2] U. Cam, “A new transadmittance type first-order allpass filter employing single third generation current conveyor,“ Analog Integrated Circuits and Signal Processing, vol. 43, pp. 97-99, 2005.

[3] S. Maheshwari, I. A. Khan, and J. Mohan, “Grounded capacitor first-order filters including canonical forms,“ Journal of Circuits, Systems, and Computers, vol. 15, no. 2, pp. 289-300, 2006.

[4] S. Maheshwari, “A canonical voltage-controlled VM-APS with a grounded capacitor, “ Circuits Syst Signal Process., vol. 27, pp. 123-132, 2008.

[5] B. Metin, O. Cicekoglu, and K. Pal, “DDCC based all-pass filters using minimum number of passive elements,“ Proc. of the MWSCAS 2007, pp. 518-521.

[6] M. Higashimura, “Current-mode allpass filter using FTFN with grounded capacitor,“ Electronics Letters, vol. 27, pp. 1182-1183, 1991.

[7] W. Tangsrirat, “Electronically tunable multi-terminal floating nullor and its applications, “ Radioengineering, vol. 17, no. 4, pp. 3-7, 2008.

[8] S. Kilinc and U. Cam, “Current-mode first-order allpass filter employing single current operational amplifier“, Analog Integrated Circuits and Signal Processing, vol. 41, pp. 47–53, 2004.

[9] L. Acosta, J.R-Angulo, A. J. L-Martín, and R. G. Carvajal, “Low-voltage first-order fully differential CMOS all-pass filter with programmable pole-zero,“ Electronics Letters, vol. 45, no. 8, pp. 385-386, 2009.

[10] U. Cam, C. Cakir, and O. Cicekoglu, “Novel transimpedance type first-order all-pass filter using single OTRA,“ Int. J. Electron. Commun. (AEÜ), vol. 58, pp. 296-298, 2004.

[11] A. Toker, S. Ozoguz, O. Cicekoglu, C. Acar, “Current-mode allpass filters using current differencing buffered amplifier and a new high-Q bandpass filter configuration,“ IEEE Trans. on Circuits and Systems-II: Analog and Digital Signal Processing, vol. 47, pp. 949-954, 2000.

[12] S. Maheshwari, “Voltage-mode all-pass filters including minimum component count circuits,” Active and Passive Electronic Components, vol. 2007, Article ID 79159, 5 pages, 2007.

[13] A. Lahiri, “Comment on “Voltage-mode all-pass filters including minimum component count circuits“,“, Active and Passive Electronic Components, vol. 2009, Article ID 595324, 4 pages, 2009.

[14] A. Ü. Keskin and D. Biolek, “Current mode quadrature oscillator using current differencing transconductance amplifiers (CDTA),“ IEE Proceedings: Circuits, Devices and Systems, vol. 153, no. 3, pp. 214-218, 2006.

[15] W. Tanjaroen and W. Tangsrirat, “Resistorless current-mode first-order allpass filter using CDTAs“, Proc. Int. Conf. ECTI-CON 2008, May 2008, Krabi (Thailand), vol. 2, pp. 721–724, 2008.

[16] C. Tanaphatsiri, W. jaikla, and M. Siripruchyanun, “An electronically controllable voltage-mode first-order all-pass filter using only single CCCDTA,“ Proc. 2008 Int. Symposium on Communications and Information Technologies (ISCIT 2008), pp. 305-309, 2008.

[17] A. Ü. Keskin, K. Pal, and E. Hancioglu, “Resistorless first-order all-pass filter with electronic tuning,“ Int. J. Electron. Commun. (AEÜ), vol. 62, pp. 304-306, 2008.

[18] V. Biolkova, Z. Kolka and D. Biolek, “Fully balanced voltage differencing buffered amplifier and its applications,“ Int. Symposium MWSCAS 2009, Cancun, 2.-5.8. 2009, accepted for publication.

[19] D. Biolek, R. Senani, V. Biolkova and Z. Kolka, “Active elements for analog signal processing: classification, review, and new proposals,” Radioengineering, vol. 17, no. 4, pp. 15–34, December 2008.

[20] OPA860 - Wide Bandwidth Operational Transconductance Amplifier (OTA) and Buffer. Texas Instruments, SBOS331C-June 2005-Revised August 2008, www.ti.com.