# Novel Resistorless Dual-Output VM All-Pass Filter Employing VDIBA

Norbert Herencsar[1], Jaroslav Koton[1], Shahram Minaei[2], Erkan Yuce[3], and Kamil Vrba[1]

[1]Brno University of Technology, Dept. of Telecommunications, Purkynova 118, 612 00 Brno, Czech Republic
herencsn@feec.vutbr.cz, koton@feec.vutbr.cz, vrbak@feec.vutbr.cz
[2]Dogus University, Dept. of Electronics and Communications Engineering, 34722 Kadikoy-Istanbul, Turkey
sminaei@dogus.edu.tr
[3]Pamukkale University, Dept. of Electrical and Electronics Engineering, 20070 Kinikli-Denizli, Turkey, Turkey
erkanyuce@yahoo.com

## Abstract

**In this paper, a new active element called voltage differencing inverting buffered amplifier (VDIBA) is presented. Using single VDIBA and capacitor a new resistorless voltage-mode first-order all-pass filter is proposed, which provides both inverting and non-inverting outputs at the same configuration simultaneously. The pole frequency of the filter can be easily controlled by means of internal transconductance. No component-matching conditions are required and it has low sensitivity. The theoretical results are verified by SPICE simulations using commercially available integrated circuit models.**

## 1. Introduction

All-pass filters are used to correct the phase shifts caused by analog filtering operations without changing the amplitude of the applied signal. In the literature, although many first-order voltage-mode (VM) all-pass filters were proposed (e.g. [1–8] and references cited therein), only circuits in [3–8] are resistorless i.e. no external resistor is required and electronically tunable. In general, the tunability feature of circuits is solved in three different ways. After the current-controlled conveyor (CCCII) was introduced [9], a new period has been opened with respect to electronic tunability in the analog filter design. Here the intrinsic X-input resistance of the CCCII is controlled via an external current, as shown in [3] and [4]. Another technique is given in [5] and [6], where the appropriate resistor is replaced by MOSFET-based voltage-controlled resistor. In recently presented voltage differencing-differential input buffered amplifier (VD-DIBA)-based VM all-pass filter [7] the tunability property of the operational transconductance amplifier (OTA) [10] is used to shift the phase response of the circuit. In fact, although the active element VD-DIBA, which belongs to the group of 'voltage differencing' elements [11], is new, it is composed of an OTA and a unity gain differential amplifier, an interconnection that is done in [8] separately. This paper reports another 'voltage differencing' element, namely the voltage differencing inverting buffered amplifier (VDIBA), which has simpler active structure than VD-DIBA [7], because there is no *v* terminal. Moreover, the proposed resistorless first-order VM all-pass filter using single VDIBA and capacitor provides both inverting and non-inverting all-pass responses simultaneously at two different output nodes. It is worth mention that only circuits in [5] and [6] have such exclusive advantage. SPICE simulation results are included to support the theory.

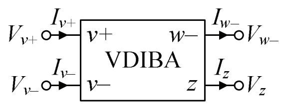
## 2. Circuit description

The voltage differencing inverting buffered amplifier (VDIBA) is a new four-terminal active device with electronic tuning, which circuit symbol and behavioral model are shown in Fig. 1. From the model it can be seen that the VDIBA has a pair of high-impedance voltage inputs $v+$ and $v-$, a high-impedance current output $z$, and low-impedance voltage output $w-$. The input stage of VDIBA can be easily implemented by a differential-input single-output OTA, which converts the input voltage to output current that flows out at the $z$ terminal. The output stage can be formed by unity-gain inverting voltage buffer (IVB). Since both stages can be implemented by commercially available integrated circuits (ICs), and moreover it contains OTA, the introduced active element is attractive for resistorless and electronically controllable circuit applications.

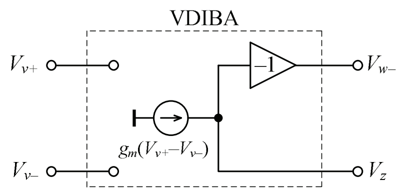
Using standard notation, the relationship between port currents and voltages of a VDIBA can be described by the following hybrid matrix:

$$\begin{bmatrix} I_{v+} \\ I_{v-} \\ I_z \\ V_{w-} \end{bmatrix} = \begin{bmatrix} 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ g_m & -g_m & 0 & 0 \\ 0 & 0 & -\beta & 0 \end{bmatrix} \begin{bmatrix} V_{v+} \\ V_{v-} \\ V_z \\ I_{w-} \end{bmatrix}, \quad (1)$$

where $g_m$ and $\beta$ represent transconductance and non-ideal voltage gain of VDIBA, respectively. The value of $\beta$ in an ideal VDIBA is equal to unity.




(a)




(b)

**Fig. 1.** (a) Circuit symbol, (b) behavioral model of VDIBA

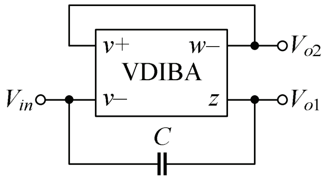



**Fig. 2.** Proposed resistorless dual-output VM all-pass filter with electronic tuning

The proposed novel first-order VM all-pass filter using single active element and capacitor is shown in Fig. 2. Considering an ideal VDIBA ($\beta = 1$), routine analysis of the circuit gives the following transfer functions (TFs):

$$T_1(s) = \frac{V_{o1}}{V_{in}} = \frac{sC - g_m}{sC + g_m}, \quad T_2(s) = \frac{V_{o2}}{V_{in}} = -\frac{sC - g_m}{sC + g_m}. \qquad (2)$$

The phase responses of the TFs are calculated as:

$$\varphi_1(\omega) = 180° - 2\tan^{-1}\left(\frac{\omega C}{g_m}\right), \quad \varphi_2(\omega) = -2\tan^{-1}\left(\frac{\omega C}{g_m}\right). \qquad (3)$$

Hence, from the above equations it can be seen that the proposed configuration can simultaneously provide phase shifting both between $\pi$ (at $\omega = 0$) to 0 (at $\omega = \infty$) and 0 (at $\omega = 0$) to $-\pi$ (at $\omega = \infty$), at output terminals $V_{o1}$ and $V_{o2}$, respectively.

From (2), the pole frequency $f_0$ is expressed as:

$$f_0 = \frac{1}{2\pi} \cdot \frac{g_m}{C}. \qquad (4)$$

Note that the $f_0$ can be easily tuned by adjusting the transconductance of VDIBA. The pole sensitivities of the proposed circuit are given as:

$$S_{g_m}^{f_0} = -S_C^{f_0} = 1, \qquad (5)$$

which are not higher than unity in magnitude.

Taking into account the non-ideal voltage gain $\beta$ of the VDIBA, TFs in (2) convert to:

$$T_1(s) = \frac{V_{o1}}{V_{in}} = \frac{sC - g_m}{sC + \beta g_m}, \quad T_2(s) = \frac{V_{o2}}{V_{in}} = -\frac{\beta sC - \beta g_m}{sC + \beta g_m}, \qquad (6)$$

and non-ideal phase responses from TFs (6) are given as:

$$\varphi_1(\omega) = 180° - \tan^{-1}\left(\frac{\omega C}{g_m}\right) - \tan^{-1}\left(\frac{\omega C}{\beta g_m}\right), \qquad (7a)$$

$$\varphi_2(\omega) = -\tan^{-1}\left(\frac{\omega C}{g_m}\right) - \tan^{-1}\left(\frac{\omega C}{\beta g_m}\right). \qquad (7b)$$

Consequently, the pole frequency of the presented filter is found as $f_0 = \beta g_m / 2\pi C$. It can be realized that the single non-ideality of the VDIBA slightly affects the filter parameters; however, this influence can be easily compensated by the transconductance of the VDIBA.

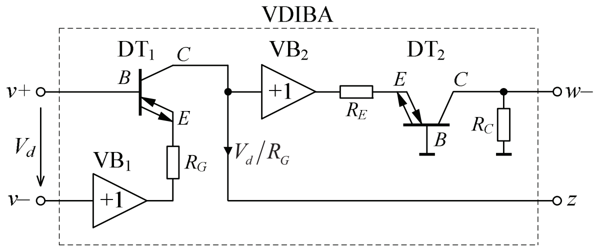



**Fig. 3.** VDIBA implementation by two ICs OPA860

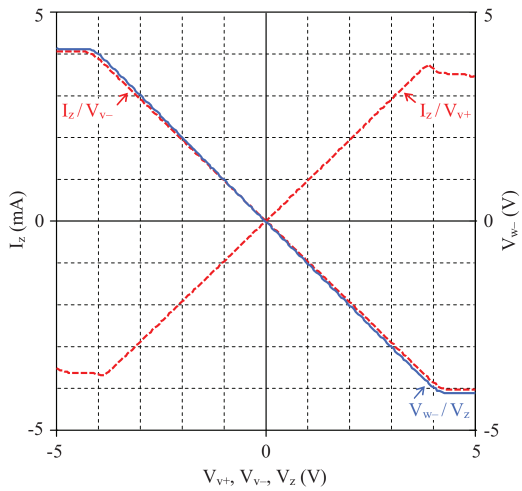


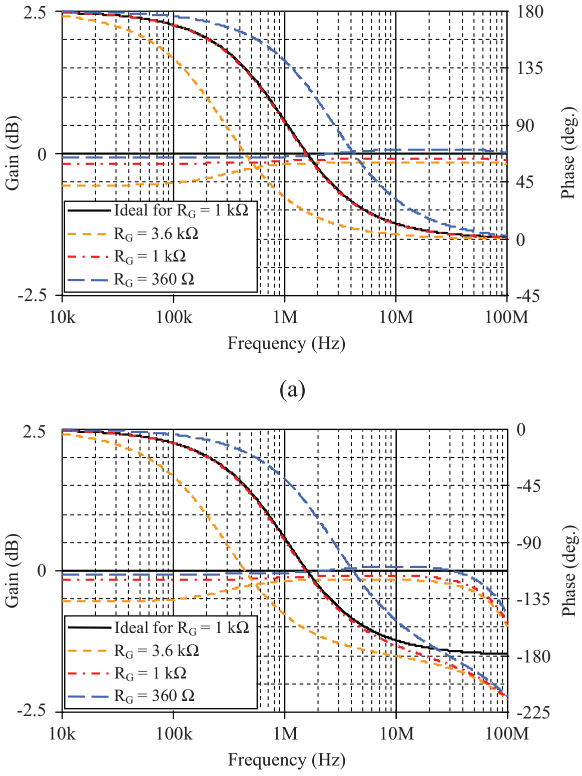

**Fig. 4.** DC analysis of VDIBA in Fig. 3: $I_z$ versus $V_{v+}$ and $V_{v-}$, $V_{w-}$ versus $V_z$

## 3. Simulation results

To verify the theoretical study, the behavior of the proposed VM all-pass filter in Fig. 2 has been further analyzed in SPICE software. Fig. 3 shows the implementation of the VDIBA using commercially available ICs OPA860 [12] by Texas Instruments and the DC power supply voltages were equal to ±5 V. The OPA860 contains the so-called 'diamond' transistor (DT) and fast voltage buffer (VB). In the input stage, in order to increase the linearity of collector current versus input voltage, the $DT_1$ is complemented with degeneration resistor $R_G \gg 1/g_{mT}$, added in series to the emitter, where the $g_{mT}$ is the DT transconductance. Then the total transconductance decreases to the approximate value $1/R_G$ [7]. In the structure shown in Fig. 3 the $VB_2$ is used to separate two stages of the VDIBA and the $DT_2$ is used as IVB, where the gain of the amplifier is calculated as $\beta \cong -R_C/R_E$ [7]. In all simulations the values of the resistors $R_E$ and $R_C$ have been chosen as 154 Ω and 169 Ω, respectively, and the value of the capacitor $C$ in the proposed filter has been selected as 150 pF.

The performance of the VDIBA was tested by DC and AC analyses. In the simulations, the value of the degeneration resistor $R_G$ was set to 1 kΩ. The DC simulation results are shown in Fig. 4. From the AC simulations, the obtained $g_m$ (for both transfers $I_z/V_{v+}$ and $I_z/V_{v-}$) of the VDIBA is approximately 0.97 mA/V with the $f_{-3dB}$ frequency 259.8 MHz. Subsequently, the obtained gain ($\beta$) of the voltage transfer $V_{w-}/V_z$ is equal to 1.002 and its $f_{-3dB}$ frequency is found to be 216.4 MHz.

Fig. 5 shows the ideal and simulated phase and gain responses illustrating the electronic tunability of the proposed filter. The pole frequency is varied for $f_0 \cong \{0.3; 1; 3\}$ MHz via the degeneration resistor $R_G = \{3.6; 1; 0.36\}$ kΩ, respectively. To illustrate the time-domain performance, transient analysis is performed to evaluate the voltage swing capability and phase errors of the filter as shown in Fig. 6. A sine-wave input of 3 V amplitude and frequency of 1 MHz was applied to the filter while keeping the $R_G = 1$ kΩ and $C = 150$ pF. Note that the output waveforms are very close to the input one. The total harmonic distortion at this frequency are found as 0.25% and 0.48% for the first and second output of the proposed filter, respectively. The total power dissipation of the circuit is found to be 246 µW.




(b)

**Fig. 5.** Electronical tunability of the pole frequency by the degenerating resistor $R_G$: (a) inverting, (b) non-inverting VM first-order all-pass filter responses

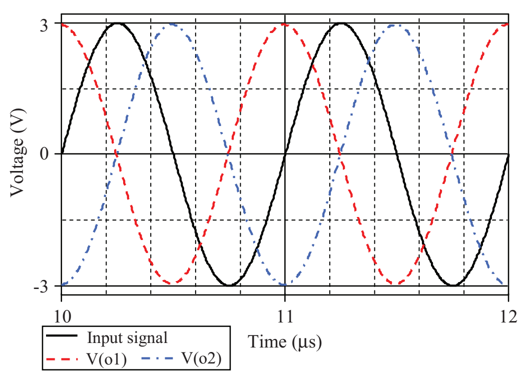



**Fig. 6.** Time-domain response of the proposed all-pass filter at 1 MHz

## 4. Conclusions

This paper presents new active element from the group of 'voltage differencing' devices, namely voltage differencing inverting buffered amplifier (VDIBA). The input part of the VDIBA is formed by the OTA, which is followed by the IVB with a gain of –1 that makes the introduced element attractive for resistorless and electronically controllable linear circuit design. As an application example a novel resistorless dual-output VM all-pass filter is proposed. SPICE simulation results confirm the feasibility of the proposed circuit.


## 5. Acknowledgment

The research described in the paper was supported by the following projects: MSM 0021630513, P102/11/P489, P102/09/1681, and FEKT-S-11-15.


## 6. References


[1] S. Maheshwari, "Analogue signal processing applications using a new circuit topology", *IET Circuits, Devices Syst.*, vol. 3, no. 3, pp. 106-115, 2009.

[2] S. Minaei and E. Yuce, "Novel voltage-mode all-pass filter based on using DVCCs", *Circuits, Syst. Signal Process.*, vol. 29, no. 3, pp. 391-402, 2010.

[3] S. Minaei and O. Cicekoglu, "A Resistorless realization of the first-order all-pass filter", *Int. J. Electron.*, vol. 93, no. 3, pp. 177-183, 2006.

[4] P. Kumar, A. U. Keskin, and K. Pal, "Wide-band resistorless allpass sections with single element tuning", *Int. J. Electron.*, vol. 94, no. 6, pp. 597-604, 2007.

[5] N. Herencsar, J. Koton, K. Vrba, and S. Minaei, "Electronically tunable MOSFET-C voltage-mode all-pass filter based on universal voltage conveyor", in *Proc. of the Int. Conf. on Computer and Communication Device – ICCCD´11*, Bali Island, Indonesia, 2011, vol. 1, pp. 53-56.

[6] N. Herencsar, J. Koton, J. Jerabek, K. Vrba, and O. Cicekoglu, "Voltage-mode all-pass filters using universal voltage conveyor and MOSFET-based electronic resistors", *Radioengineering*, vol. 20, no. 1, pp. 10-18, 2011.

[7] D. Biolek and V. Biolkova, "First-order voltage-mode all-pass filter employing one active element and one grounded capacitor", *Analog Integr. Circuits Signal Process.*, vol. 65, no. 1, pp. 123-129, 2010.

[8] A. U. Keskin, K. Pal, and E. Hancioglu, "Resistorless first order all-pass filter with electronic tuning", *Int. J. Electron. and Commun. (AEU)*, vol. 62, no. 4, pp. 304-306, 2008.

[9] A. Fabre, O. Saaid, F. Wiest, and C. Boucheron, "High frequency applications based on a new current controlled conveyor", *IEEE Trans. on Circuits Systems–I*, vol. 43, no. 2, pp. 82-91, 1996.

[10] R. L. Geiger and E. Sanchez-Sinencio, "Active filter design using operational transconductance amplifiers: a tutorial", *IEEE Circuits Devices Mag.*, vol. 1, pp. 20-32, 1985.

[11] 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. 15-32, 2008.

[12] Datasheet OPA860 – Wide Bandwidth Operational Transconductance Amplifier (OTA) and Buffer. Texas Instruments, SBOS331C–June 2005–Rev. August 2008.