The VDDDA in Multifunction Filter With Mutually Independent Q and ω_0 Control Feature

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Abstract

The paper focuses on the application possibilities of the newly presented voltage differencing active building block called voltage differencing differential difference amplifier - VDDDA. Using this active element, a multifunction frequency filter is designed featuring the possibility of mutually independent control of quality factor Q and characteristic frequency ω_0 by means of active elements. The structure of the filter is based on the idea of the Akerberg-Mossberg (AM) filter, i.e. the integrators in the structure are always realized only by two active elements. This fact results in better phase compensation for the filter. Compared to the AM opamp based filter, the newly proposed structure features high-impedance inputs, low-impedance output, and all basic frequency responses. The performance of the proposed structure has been verified by SPICE simulations using the TSMC 0.18 μm level-7 SCN018 CMOS process parameters with ± 0.9 V supply voltage.

1. Introduction

The research in analog signal processing is significantly considered in the analyses and application possibilities of different active building blocks (ABB) that are expected to have better features that conventional operational amplifier (opamp). Probably, the most discussed ABBs have been the current conveyors, their three generations CCI [1], CCII [2], CCIII [3], and different types, such as differential voltage CC (DVCC) [4], differential difference CC (DDCC) [5], or dual-X CC (DXCCII) [6] mentioned as examples. Although in the group of CCs also types featuring electronic tuneability (e.g. current controlled CC (CCCII) [7], electronically tunable CC (ECCII) [8]) can be found, the current research in the active element design focuses more on the ABBs that use a transconductance amplifier (OTA) in the internal structure. To this group belongs the current differencing transconductance amplifier (CDTA) [9], current conveyor transconductance amplifier (CCTA) [10], current follower transconductance amplifier (CFTA) [11], voltage differencing buffered amplifier (VDBA), voltage differencing transconductance amplifier (VDTA), voltage differencing current conveyor (VDCC) [12], voltage differencing-differential input buffered amplifier (VD-DIBA) [13], or voltage differencing inverting buffered amplifier (VDIBA) [14].

Newly, another 'voltage differencing' active building block labeled as VDDDA (voltage differencing differential difference amplifier) has been presented in [15] and whose possible usage was shown on the design of a simple first order all-pass filter. Anyway, the frequency filters are usually designed as multifunction circuits, i.e. more signal responses are available in single topology. Probably the most known multifunction filter is the KHN (Kerwin-Huelsman-Newcomb) structure [16]. A number of voltage- and current-mode KHN equivalent structures can be found in the literature, e.g. [17]–[20]. The KHN structures generally enable mutually independent control of the quality factor Q and natural frequency ω_0 by means of either the passive or active elements used, and feature with low-, band- and high-pass frequency responses. Another multifunction filter is e.g. the Tow-Thomas structure [21]. In these configurations, the internal loops with integrators are always realized by two and three active elements.

From the viewpoint of better phase compensation for the filter when high-frequency effects of the active elements are considered, the Akerberg-Mosseberg (AM) topology is more suitable [21]. In the AM topology, to realize the non-inverting integrator, one of the operational amplifiers is used as a feedback element that a feedforward as it is done e.g. in the Tow-Thomas structure [21]. As a consequence, in the AM topology the feedback loops include always only two active elements. Based on this idea, a multifunction frequency filter using VDDDA as active elements is presented in this paper. The function block features the possibility of mutually independent control of the quality factor Q and natural frequency ω_0 by means of appropriate active elements' parameter. The multifunction filter employs three active elements, and three passive elements, all grounded. Using the CMOS implementation of the active elements, simulation results that fully support the theoretical conclusions are given.

2. VDDDA Description

The VDDDA is a seven-terminal active element, which circuit symbol and behavioral model are shown in Fig. 1(a) and Fig. 1(b), respectively. From the behavioral model, it can be seen that the VDDDA suitably combines the differential-input

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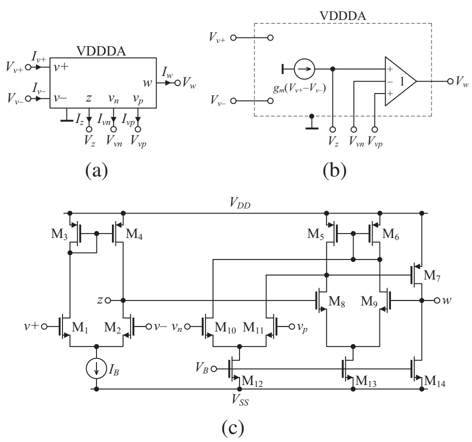

Figure 1. (a) Circuit symbol, (b) behavioral model, (c) CMOS implementation of VDDDA.

OTA [22] and differential difference amplifier (DDA) [23]. The VDDDA has a pair of high-impedance voltage inputs $v+$ and $v-$, a high-impedance current output z, a high-impedance voltage inputs v_p and v_n, and a low-impedance voltage output w. The relationship between the terminal voltages and currents can be described by the following equations:

$$\begin{bmatrix} I_{v+} \\ I_{v-} \\ I_z \\ I_{vn} \\ I_{vp} \\ V_w \end{bmatrix} = \begin{bmatrix} 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ g_m & -g_m & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & \beta_1 & -\beta_2 & \beta_3 & 0 \end{bmatrix} \begin{bmatrix} V_{v+} \\ V_{v-} \\ V_z \\ V_{vn} \\ V_{vp} \\ I_w \end{bmatrix} \quad (1)$$

where g_m and $\beta_i = 1 - \varepsilon_{vi}$ for $i = 1, 2, 3$ represent the transconductance and non-ideal voltage gains of the VDDDA, whereas $|\varepsilon_{vi}| << 1$ are the voltage tracking errors. Assuming an ideal VDDDA, the voltage gains β_i are equal to unity.

The CMOS implementation of the VDDDA used for the SPICE simulations is given in Fig. 1(c).

3. Multifunction Filter Analysis

The proposed multifunction frequency filter based on the idea of Akerberg-Mosseberg topology is shown in Fig. 2. The feedback loops are always realized by only two active elements: VDDDA_1-VDDDA_2 and VDDDA_2-VDDDA_3. Based on the connected input and output response, the voltage transfers can be expressed as follows:

$$\frac{V_{01}}{V_{in1}} = \frac{-sg_{m1}g_{m2}C_2}{s^2C_1C_2G_x + sg_{m1}g_{m2}C_2 + g_{m2}g_{m3}G_x}, \quad (2a)$$

$$\frac{V_{01}}{V_{in2}} = \frac{g_{m1}g_{m2}g_{m3}}{s^2C_1C_2G_x + sg_{m1}g_{m2}C_2 + g_{m2}g_{m3}G_x}, \quad (2b)$$

$$\frac{V_{01}}{V_{in3}} = \frac{s^2C_1C_2g_{m1}}{s^2C_1C_2G_x + sg_{m1}g_{m2}C_2 + g_{m2}g_{m3}G_x}, \quad (2c)$$

$$\frac{V_{02}}{V_{in2}} = \frac{g_{m2}g_{m3}G_x}{s^2C_1C_2G_x + sg_{m1}g_{m2}C_2 + g_{m2}g_{m3}G_x}, \quad (2d)$$

$$\frac{V_{02}}{V_{in3}} = \frac{s^2C_1C_2G_x}{s^2C_1C_2G_x + sg_{m1}g_{m2}C_2 + g_{m2}g_{m3}G_x}, \quad (2e)$$

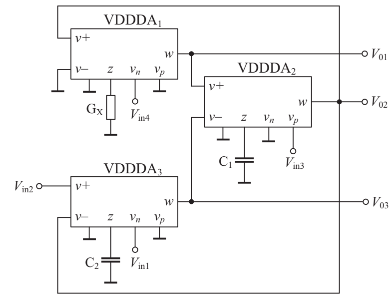

Figure 2. Proposed multifunction filter using VDDDAs.

$$\frac{V_{03}}{V_{in3}} = \frac{-sC_1g_{m3}G_x}{s^2C_1C_2G_x + sg_{m1}g_{m2}C_2 + g_{m2}g_{m3}G_x}, \quad (2f)$$

$$\frac{V_{03}}{V_{in4}} = \frac{g_{m2}g_{m3}G_x}{s^2C_1C_2G_x + sg_{m1}g_{m2}C_2 + g_{m2}g_{m3}G_x}, \quad (2g)$$

where it can be clear that according to (2b), (2d), or (2g) a low-pass, to (2a) or (2f) a band-pass, and to (2c) or (2e) a high-pass response can be directly obtained. All voltage responses are sensed directly on the corresponding voltage output w of the active element. The w-terminal behaves as a voltage source and hence the voltage response is independent on the load impedance.

Here, it should be noted that mainly using the DDA part of the active element, the input signal is always connected to a high-impedance node, and therefore no additional active element is needed. Using this advantage, by simply interconnecting the terminals V_{in2} and V_{in3}, at the output V_{02} according to (2d) and (2e) a band-reject is obtained. Similarly, interconnecting the terminals V_{in1}, V_{in2} and V_{in3}, according to (2a), (2b), and (2c) at the output V_{01} an all-pass filter can be realized.

From the denominator of the transfer function (2), the quality factor Q and natural frequency ω_0 can be derived as:

$$Q = \sqrt{\frac{C_1g_{m3}}{C_2g_{m2}}} \cdot \frac{G_x}{g_{m1}}, \quad (3)$$

$$\omega_0 = \sqrt{\frac{g_{m2}g_{m3}}{C_1C_2}}. \quad (4)$$

Assuming $g_{m2} = g_{m3} = g_m$ (3) and (4) simplify to:

$$Q = \sqrt{\frac{C_1}{C_2}} \cdot \frac{G_x}{g_{m1}}, \quad (5)$$

$$\omega_0 = g_m\sqrt{\frac{1}{C_1C_2}}. \quad (6)$$

From (5) and (6), the quality factor Q can be electronically adjusted by g_{m1} without affecting natural frequency, and similarly varying g_m (assuming $g_{m2} = g_{m3} = g_m$), the ω_0 can be tuned without changing the value of Q.

Varying the transconductances while tuning Q or ω_0 of the filter, the gain in the pass-band of the low-pass transfer functions (2d) and (2g), of the band-pass transfer function (2a), of the high-pass response (2e), and of the stop-band response at the output V_{02} (see the text above) stays constant and is unity.

4. Simulation Results

To verify the behavior of the proposed multifunction frequency filter, the structure from Fig. 2 has been further analyzed by SPICE simulations. The transistor parameters used for

Table 1. Parasitic impedances of VDDDA.

C_{v+}	56.6 fF
C_{v-}	43.3 fF
$R_z \| C_z$	282.6 kΩ‖20.9 fF
C_{vp}, C_{vn}	9.4 pF
$R_w + L_w$	458 Ω + 0,58 μH

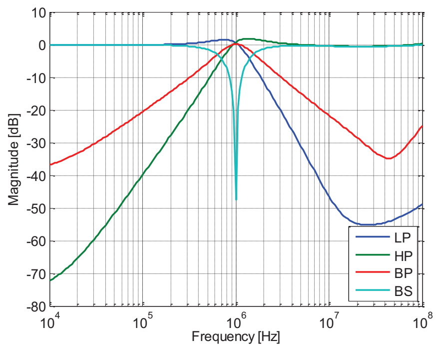

Figure 3. Frequency responses of the multifunction filter.

the simulations are taken from TSMC 0.18 μm level-7 SCN018 process ($V_{\mathrm{THn}} = 0.3725$ V, μ_n = 259.5304 cm^{2}V^{-1}s^{-1}, $V_{\mathrm{THp}} = -0.3948$ V, μ_p = 109.9762 cm^{2}V^{-1}s^{-1}, $T_{\mathrm{ox}} = 4.1$ nm) [24]. The aspect ratios of NMOS and PMOS transistors from the internal CMOS implementation of the VDDDA (Fig. 1(c)) are $(W/L)_{1,2} = 9\ \mu\mathrm{m}/1.08\ \mu\mathrm{m}$, $(W/L)_{3,4} = 3.96\ \mu\mathrm{m}/1.08\ \mu\mathrm{m}$, $(W/L)_{5,6,7} = 3.6\ \mu\mathrm{m}/0.18\ \mu\mathrm{m}$, $(W/L)_{8,9,10,11} = 0.72\ \mu\mathrm{m}/1.08\ \mu\mathrm{m}$, $(W/L)_{12,,13,14} = 2.16\ \mu\mathrm{m}/1.08\ \mu\mathrm{m}$. The supply voltage is ± 0.9 V and bias voltage is $V_{\mathrm{B}} = -0.35$ V. Basic DC and AC performance of the VDDDA was analyzed in [15], where it is stated that the maximum operating frequency is 142.51 MHz. Here, we additionally present the parasitic impedances of the VDDDA that are summarized in Table 1.

The values of the passive elements in the filter were selected as follows: $R_X = 2.1$ kΩ, $C_1 = C_2 = 47$ pF. Varying the bias current $I_B = \{20, 50, 125\}$ μA, according to [22] and the transistor parameters the transconductance of VDDDA is $g_m = \{190, 300, 474\}$ μS.

In Fig. 3, the low-pass (2g), high-pass (2e), band-pass (2a), and band-stop response at the voltage output V_{02} are shown. The values of the bias currents are $I_{B1} = 125$ μA and $I_{B2} = I_{B3} = 50$ μA, which corresponds to the value of quality factor $Q = 1$, and pole frequency $f_0 = 1$ MHz.

The simulation results from Fig. 4 show the feature of angular frequency tuning by means of the active elements. Here, the quality factor is set to be unity ($Q = 1$) and the bias currents of the VDDDA$_2$ and VDDDA$_3$ are changed, while $I_{B2} = I_{B3} = I_B$. For $I_B = \{20, 50, 125\}$ μA, the pole frequency f_0 reaches the values of approx. 643 kHz, 1 MHz, and 1,6 MHz, respectively.

In Fig. 5 the possibility of adjusting the quality factor is shown. The pole frequency is 1 MHz ($I_B = 50$ μA) and for $I_{B1} = \{20, 50, 125\}$ μA the quality factor has the value of 2.5, 1.6 and 1.0, respectively. It should be noted, as the transconductance g_m of the active element is proportional to the square root of the bias current, the reasonable tunning range of the pole-frequency f_0 and quality factor Q will be never broader than one decade.

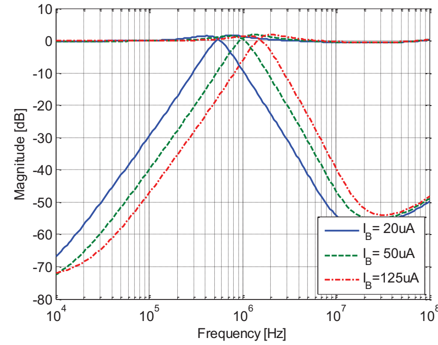

Figure 4. Tuning the pole frequency while keeping the Q-factor constant.

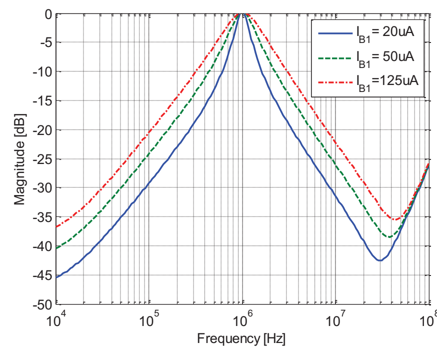

Figure 5. Adjusting the Q-factor while keeping the pole frequency constant.

To show the stability of the proposed filter, transient responses of the the low-pass (2g), high-pass (2e), band-pass (2a) to the 1 MHz input signal of 50 mV amplitude are given Fig. 6.

To analyze the dynamic performance of the filter, the total harmonic distortion of the low-pass response (2g) has been evaluated (Fig. 7). The bias currents of the VDDDAs are $I_{B1} = 125$ μA, $I_{B2} = I_{B3} = 50$ μA. It can be seen from the graph that for input signal amplitudes up to 410 mV the THD value stays below 0.5 %.

5. Conclusion

It this paper, the application possibilities of the newly presented active element, namely the voltage differencing differential difference amplifier - VDDDA, have been shown on the design of a multifunction frequency filter. The proposed circuit is based on the Akerberg-Mosseberg topology that is generally advantageous in better phase compensation. The filter uses three active and three passive elements, all grounded. The main feature of the filter is the possibility of mutually independent control of quality factor Q and characteristic frequency ω_0 by means of active elements. Using the advantage of the VDDDA, the input signal is always connected to the high-impedance input while the output voltage response is taken at a low-impedance output. Using the CMOS implementation of the active elements, the performance of the proposed structure was verified by SPICE simulations that are in very good agreement with the theoretical presumptions.

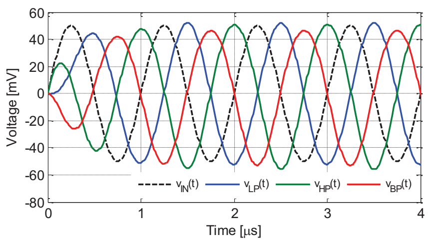

Figure 6. Transient responses of the the low-pass (2g), high-pass (2e), band-pass (2a)

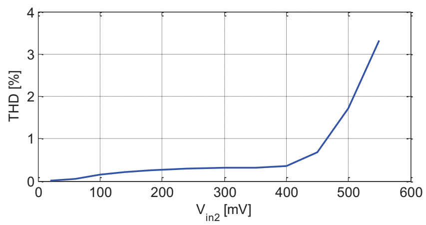

Figure 7. THD of the low-pass response (2g).

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