Current-mode tunable and adjustable filter with digitally adjustable current amplifier and transconductance amplifiers

Jan Jerabek, and Kamil Vrba

***Abstract*—**A multifunctional filter with Digitally Adjustable Current Amplifier (DACA), two balanced transconductance amplifiers (OTAs) and two passive elements is presented in this paper. The natural frequency of the filter is tunable, quality factor is adjustable, filter is of the single-input multiple-output (SIMO) type, and operates in the current mode. The contribution contains simulation results that were obtained with the help of behavioral model of the UCC-N1B 0520, UVC-N1B 0520 and EL2082 elements and also measurement results. The presented simulation results prove the quality of designed filter.

***Keywords*—**BOTA, current mode, DACA, filter.

I. Introduction

ANALOG frequency filters in the current mode [1] with various types of active elements still attract many researchers' attention. Many different types of active elements are used in filtering circuitries, starting from simple current followers (CF) [2], [3], through dual- or multiple-output current followers (DO-CF, MO-CF) [4], [5], OTA amplifiers, mostly in the form of the OTA-C filter [6], [7], also current conveyors (CC) of different generations [8], [9] up to more complex active elements such as the Current Differencing Transconductance Amplifier (CDTA) [10] – [12], which consists of a differential current follower and a transconductance amplifier, and finally the Current Follower Transconductance Amplifier (CFTA) [13], which contains a simple current follower and also a transconductance amplifier.

The combination of digitally adjustable current followers and transconductance amplifiers is really advantageous for the design of filtering structures in the current mode. This contribution is therefore focused on the utilization of the above elements. The benefits of the solution presented are: simplicity (only two closed loops are present in the circuit), multifunctionality (four types of transfer functions are obtainable), tunability of natural frequency, adjustability of the quality factor and relative sensitivities to all parameters of the filter are low. The circuitry designed is of the Single Input Multiple Output (SIMO) type, which provides the advantage of a single and fixed input node. Both passive elements are grounded. All the features mentioned form good conditions for the application of this structure.

II. Active Elements

The designed filter includes two types of active elements. The first of them is the Digitally Adjustable Current Amplifier (DACA) [14], [15] which schematic symbol is shown in Fig. 1a. This element is under the development on our workplace in cooperation with ON Semiconductor inc. and first samples will be available before the end of 2010. Therefore DACA is temporary replaced by the block shown in Fig. 1b for test purposes. Structure consists of three active elements, first of them is the Universal Voltage Conveyor (UVC) [16], second is the multiplier EL2082 [17] and third is the Universal Current Conveyor (UCC) [18]. UVC and UCC were developed on our workplace in 2005. UVC in structure presented in Fig. 2b forms the input stage that makes the difference between two input currents. EL2082 provides the amplification of differential current and finally, UCC forms the output stage by multiplying the number of current outputs. If we define differential input as follows

$$I_{\mathrm{dif\_IN}} = I_{\mathrm{IN+}} - I_{\mathrm{IN-}} \,, \tag{1}$$

then behavior of the DACA could be described by the relation

$$I_{\mathrm{OUT1+}} = I_{\mathrm{OUT2+}} = -I_{\mathrm{OUT1-}} = -I_{\mathrm{OUT2-}} = A_{\mathrm{I}}\, I_{\mathrm{dif\_IN}} \,, \tag{2}$$

where A_{I} represents current gain, which value could be controlled digitally in case of planned DACA, nevertheless in case of structure shown in Fig. 2b by voltage level (Vgain). Amplification of the block is limited to range {0; 3.5}.

The second type of active element is the well-known Balanced Operational Transconductance Amplifier (BOTA). The BOTA schematic is shown in Fig. 1c. Relations that describe the BOTA behavior are

$$\boldsymbol{I}_{\mathrm{OUT+}} = -\boldsymbol{I}_{\mathrm{OUT-}} = g_{\mathrm{m}}(\boldsymbol{U}_{\mathrm{IN+}} - \boldsymbol{U}_{\mathrm{IN-}}) \,. \tag{3}$$

Manuscript received September 30, 2010. The research described in this paper was supported by Czech Science Foundation projects No. 102/09/1681 and No. 102/08/H027, by the Czech Ministry of Education under the research program MSM 0021630513 and by the internal grant of Faculty of Electrical Engineering and Communication, Brno University of Technology, No. FEKT-S-10-16.

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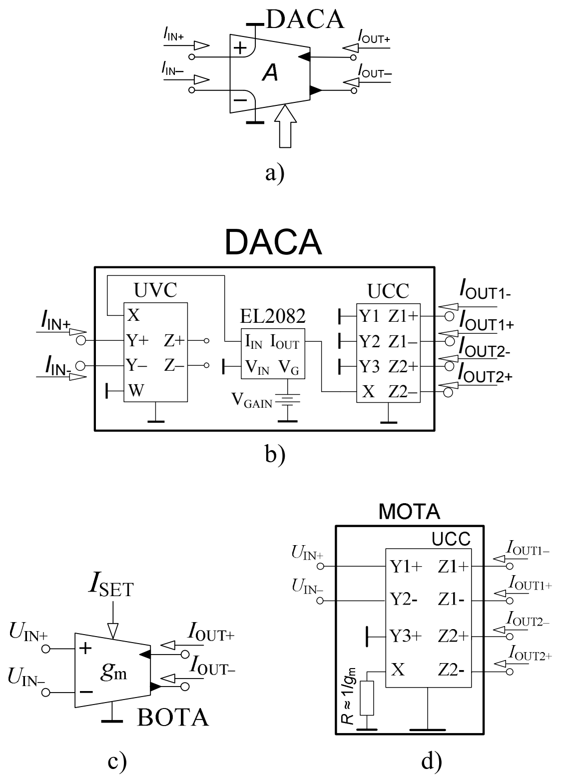


Fig. 1. a) Schematic of the Digitally Adjustable Current Amplifier (DACA) b) Model of the DACA element with four output nodes c) Schematic of the Balanced Operational Transconductance Amplifier (BOTA) d) Circuitry forming BOTA (or MOTA) with the help of one Universal Current Conveyor (UCC)

We can compile the BOTA element by many ways, from two simple OTAs for instance. Multiple-output OTA (MOTA) could be formed by the structure shown in Fig. 1d. It is obvious that one UCC and one resistor are sufficient enough to produce a BOTA or MOTA. The transconductance of such a connection of the UCC circuit is equal to $g_m \approx 1/R$.

III. DESIGNED FILTER

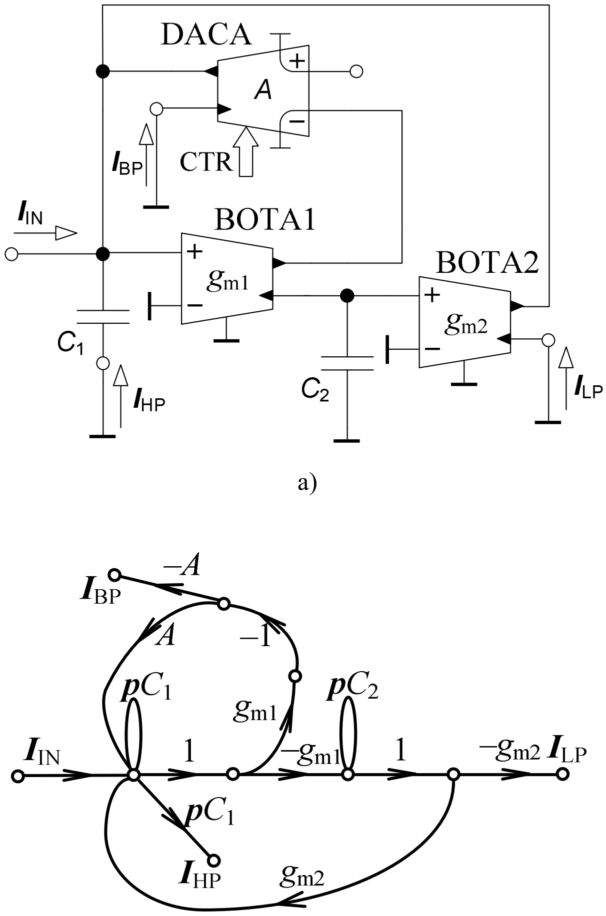


Fig. 2 a) Designed universal filter formed by two closed loops with two BOTA and one DACA b) Simplified M-C signal flow graph (SFG) of the circuit

The multifunctional second-order filtering structure with a minimum number of passive components, included possibility of tuning the natural frequency and adjusting of the quality factor was the goal of the design. Possible circuits were analyzed by the SFG method and one of the solutions obtained is depicted in Fig. 2a. Purposely there are only balanced dual-output active elements in the circuitry. It is beneficial when designing fully differential filter from the single ended topology, but this is not included in this contribution. Presented filter consists of just three active elements. If the filter should be universal, one additional active element would be required or one of active elements should not have balanced output. The simplified M-C SFG of the circuit from Fig. 2a is shown in Fig. 2b in order to illustrate the principle behavior of the circuit. The final circuit contains two grounded capacitors, no resistors are present; they are replaced by the transconductance of the BOTA elements.

The transfer functions of the designed circuit are given by

$$\frac{\boldsymbol{I}_{LP}}{\boldsymbol{I}_{IN}} = \frac{g_{m1} g_{m2}}{\boldsymbol{D}}, \quad \frac{\boldsymbol{I}_{BP}}{\boldsymbol{I}_{IN}} = \frac{\boldsymbol{s} C_2 g_{m1} A}{\boldsymbol{D}}, \tag{3, 4}$$

$$\frac{\boldsymbol{I}_{HP}}{\boldsymbol{I}_{IN}} = \frac{\boldsymbol{s}^2 C_1 C_2}{\boldsymbol{D}}, \quad \frac{\boldsymbol{I}_{BS}}{\boldsymbol{I}_{IN}} = \frac{\boldsymbol{I}_{HP} + \boldsymbol{I}_{LP}}{\boldsymbol{I}_{IN}} = \frac{\boldsymbol{s}^2 C_1 C_2 + g_{m1} g_{m2}}{\boldsymbol{D}}, \tag{5, 6}$$

where

$$\boldsymbol{D} = \boldsymbol{s}^2 C_1 C_2 + \boldsymbol{s} C_2 g_{m1} A + g_{m1} g_{m2} = 0. \tag{7}$$

The abbreviations IN, LP, BP, HP and BS stand for input, low pass, band pass, high pass and band stop filtering functions, respectively. It is obvious that the designed filter is multifunctional, because an appropriate selection of output or outputs enables operation as one of the four standard filtering functions. The natural frequency and quality control could be controlled mutually independently. The natural frequency could be controlled by a simultaneous change of g_{m1} and g_{m2}. The quality factor could be simply controlled by the change of gain A.

Eq. (3) – (7) are valid without any condition. The pass-band gain is unity (0 dB) for each transfer function type.

IV. SENSITIVITY ANALYSIS

The angular frequency and the quality factor are for all transfer functions expressed from (7) by

$$\omega_0 = \sqrt{\frac{g_{m1} g_{m2}}{C_1 C_2}}\ ,\ Q = \frac{1}{A}\sqrt{\frac{g_{m2} C_1}{g_{m1} C_2}}\ . \qquad (8, 9)$$

The relative sensitivities of the angular frequency and of the quality factor to individual components are equal to

$$S_{g_{m1}}^{\omega_0} = S_{g_{m2}}^{\omega_0} = S_{g_{m2}}^{Q} = S_{C_1}^{Q} = 0.5, \qquad (10)$$

$$S_{C_1}^{\omega_0} = S_{C_2}^{\omega_0} = S_{C_2}^{Q} = S_{g_{m1}}^{Q} = -0.5, \qquad (11)$$

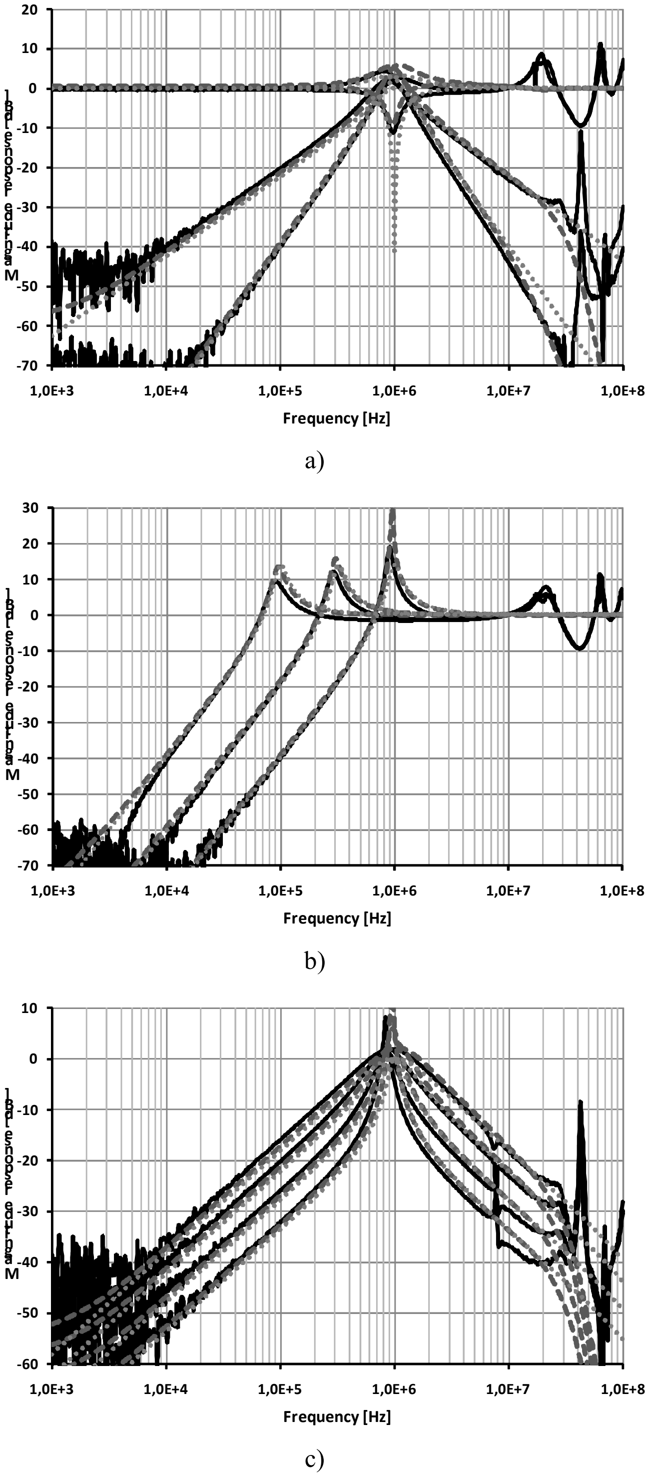
$$S_{A}^{Q} = -1\ . \qquad (12)$$

From eq. (10)–(12) it is obvious that all relative sensitivities are very low.

V. SIMULATION AND MEASUREMENT RESULTS

The proposed numerical parameters of the filter were as follows: $f_0 = \{0.1; 1\}$ MHz, $Q = \{0.707; 5\}$ transconductances $g_{m1} = g_{m2} = g_m = \{0.196; 1.96\}$ mS and $A = \{0.5; 3.5\}$. The calculated values of capacitors are $C_2 = g_m/(\omega A Q) \approx 126$ pF, $C_1 = (g_m^2)/(C_2\omega^2) \approx 780$ pF. Third-order behavioral models of the UCC-N1B and UVC-N1B were used for simulation purposes [19] together with third-order spice model of EL2082. These models are quite accurate in AC simulations and with their help we can faithfully verify features of the filter. Measurement was done with UCC-N1B 0520 chip connected as MOTA, as was shown in Fig. 1d and with DACA that was formed by three active elements as shown in Fig. 1b.

The first graph (Fig. 3a) contains magnitude responses of the HP, BS, LP and BP filter types for the natural frequency 1 MHz and the quality factor $Q = 1.2$. Theoretical responses are depicted by dotted grey lines, PSpice simulation results by dashed dark-grey lines and measurement results by solid black lines. Theoretical, simulated and measured responses are quite similar. Differences at higher frequencies are mostly caused by the limited bandwidth of the combined DACA element which bandwidth is approximately 10 MHz. The graph in Fig. 3b represents the tuning of pole frequency in the case of the HP function, which was obtained by a simultaneous change of g_{m1} and g_{m2}. Three pole frequencies ($f_1 = 100$ kHz; $f_2 = 320$ kHz; $f_3 = 1$ MHz) are obtained by the transconductances: 196 µS; 625 µS; 1.96 mS. There is no significant drop in the pole frequency. The last plot shows the adjustment of the quality factor in case of BP filter tuned to natural frequency 1 MHz. Adjusting is controlled by the gain of DACA element ($A = 3.5$, 2, 1, 0.5) which produced quality factor ($Q = 0.7$, 1.2, 2.5, 4.9).



a)

b)

c)

Fig. 3 Simulation results a) Magnitude responses of the LP, HP, BP and BS filters for the characteristic frequency 340 kHz b) Tuning of the natural frequency ($f_1 = 100$ kHz; $f_2 = 320$ kHz; $f_4 = 1$ MHz) in case of the LP filter. c) Tuning of the quality factor in case of the BP filter ($Q = 0.7$, 1.2, 2.5, 4.9) dotted grey lines – theoretical assumptions, dashed dark-grey lines – simulation results, solid black lines – measurement results.

VI. CONCLUSION

A multifunctional filter with three active elements and two passive components was presented in this paper. It was demonstrated that the pole frequency could be tuned easily by a simultaneous change of the transconductance of both OTAs and the quality factor could be adjusted by the gain of DACA element. The filter is of the SIMO type. There is no resistor in the structure, therefore it can be considered as the OTA-C type combined with DACA. Good characteristics of the designed filter were verified via the simulation with good-quality models and by measurement. Nevertheless, we are looking forward for first samples of currently developed single-chip DACA element that should improve results in significant way.

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