Comparison of the Fully-Differential and Single-Ended Solutions of the Frequency Filter with Current Followers and Adjustable Current Amplifier

Jan Jerabek and Kamil Vrba
Department of Telecommunications, Faculty of Electrical Engineering and Communication
Brno University of Technology
Purkynova 118, 612 00 Brno, Czech Republic
Emails: jerabekj@feec.vutbr.cz, vrbak@feec.vutbr.cz

***Abstract*—Two solutions of universal and adjustable current-mode filters are presented in this contribution. The first of them is able to process single-ended (S-E) signals in communications and the other can operate fully-differentially (F-D) and therefore is well applicable for balanced transmission lines. Both circuits have adjustable quality factor and both are analyzed in this contribution. Their simulation results are compared to each other. Main contribution of this paper is the presentation of two novel solutions and their mutual comparison.**

Keywords-adjustable amplifier; DACA; fully-differential.

I. INTRODUCTION

F-D structures [1]–[10], usually used on balanced communication lines, have several benefits when compared to the single-ended (S-E) circuits. It is, for instance, higher dynamic range of the signals, high attenuation of common-mode signal, better power supply rejection ratio, and lower harmonic distortion. F-D structures also have some disadvantages. They are, in particular, larger area needed on the chip, which is related to greater power consumption, and sometimes the design of F-D structures is more complex with respect to S-E topologies.

The basics of the design of simple F-D structures with a high Common Mode Rejection Ratio (CMRR) (by coupling two S-E structures) were described in [1]. Transconductance elements such as the Balanced Operational Transconductance Amplifier (BOTA) [2] are very often present in F-D filters. Differential-input buffered and transconductance amplifiers (DBTA) [3] can also be applied, for instance. The Fully Differential Current Feedback Operational Amplifier (FDCFOA) operating in the voltage mode and having various internal structures is also quite common [4]; for example fully-differential current conveyors of the second generation (FDCCII) [5]–[7] or fully-differential current followers (FD-CF) [9], [10]. The structures traditionally work in the voltage-mode (VM); however, recent research is also focused on the current-mode (CM) filters. Various conceptions of simple F-D circuits capable of processing current-mode signals can be found in [8], while the methodology for the F-D filter design with various target requirements was presented in [11].

Recently, current followers with non-unity gain [12] or current amplifiers [13], [14] have been presented and should be suitable for high-frequency applications. In [9], [15], [16], the Digitally Adjustable Current Amplifier (DACA) has been presented.

The newly designed structure of the universal filter working in the current mode is compared with its F-D equivalent in this contribution. Both solutions provide the possibility of digital adjustment of the quality factor. Multiple-output current follower (MO-CF) [17], [18], its fully-differential equivalent, Fully-Differential Current Follower (FD-CF), and DACA are used as active elements. The main aim of this work is to compare these F-D and S-E solutions, because this approach is not so common.

Contribution is organized as follows: Section II provides short description of active elements; Section III includes designed filters and Section IV summarizes simulation results.

II. ACTIVE ELEMENTS DEFINITIONS

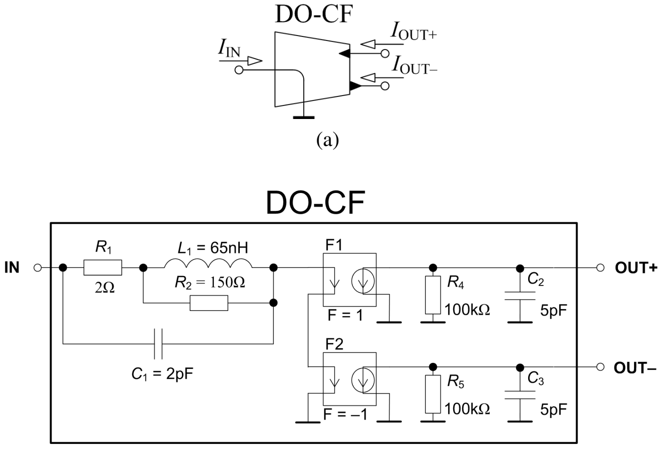
The S-E and F-D structures presented in this contribution operate with three types of active element. One is a simple current active follower with dual or multiple outputs (DO-CF, MO-CF) [17]. As an example, the DO-CF schematic symbol is shown in Fig. 1a, and its simple 3rd-level simulation model suitable for AC analysis is shown in Fig. 1b. This model covers only input and output impedances. Ideally, the current transfer from an input to an output is unity, with inverted or non-inverted phase of the signal.

The F-D equivalent of the DO-CF circuit is the Fully-Differential Current Follower (FD-CF), which is suitable for fully-differential signal processing. It has at least four outputs, two with positive current transfer and two with negative current transfer from the input nodes. The FD-CF schematic symbol is shown in Fig. 2a, a simple 3rd-order AC simulation model is shown in Fig. 2b. The ideal FD-CF is described by

$$I_{\mathrm{OUT1+}} = I_{\mathrm{OUT2+}} = (1/2)(I_{\mathrm{IN+}} - I_{\mathrm{IN-}}), \qquad (1)$$

$$I_{\mathrm{OUT1-}} = I_{\mathrm{OUT2-}} = -(1/2)(I_{\mathrm{IN+}} - I_{\mathrm{IN-}}). \qquad (2)$$

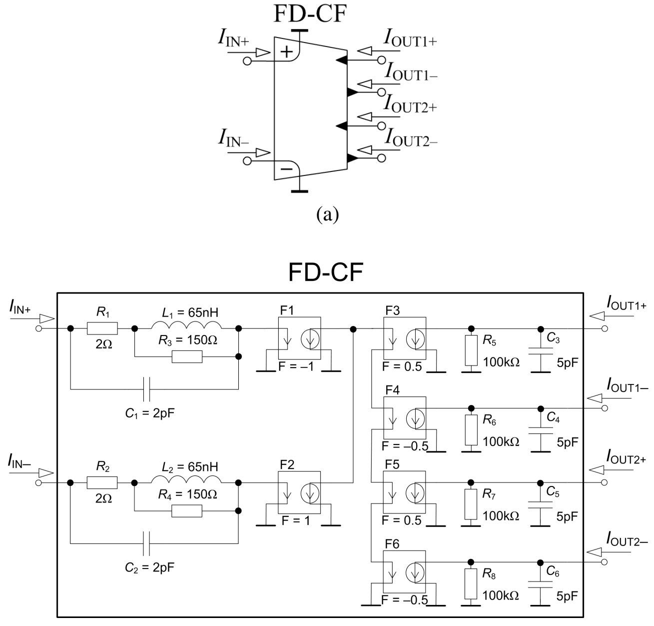
ISBN: 978-1-61208-183-0



(a)

(b)

Figure 1. Dual-Output Current Follower (DO-CF): (a) schematic symbol (b) 3rd-order AC simulation model

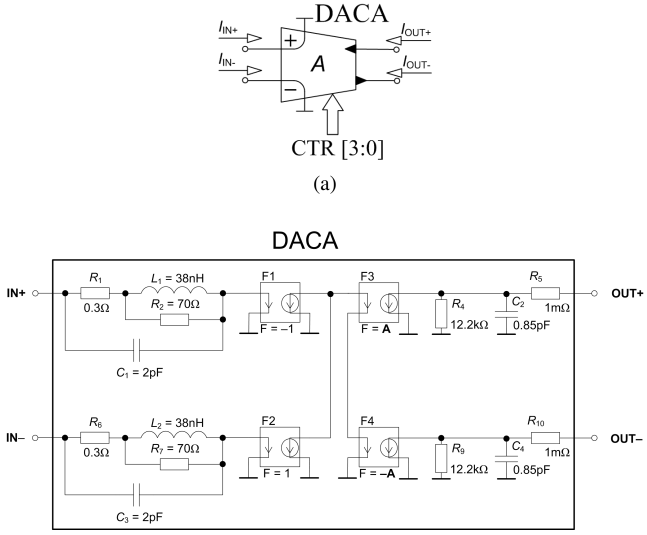


(a)

(b)

Figure 2. Fully-Differential Current Follower (FD-CF): (a) schematic symbol (b) 3rd-order AC simulation model

A Digitally Adjustable Current Amplifier (DACA) (Fig. 3a) is the other active element. The key feature of DACA is that current gain (A) is adjustable and can be controlled by three-bit digital bus. The DACA circuit was lately developed in cooperation with ON Semiconductor in the CMOS 0.35 μm technology. We have several samples from the second test batch available and they are currently undergoing the first tests. The DACA 3rd-level AC simulation model is depicted in Fig. 3b. The current transfers of the DACA element are given by the relations



(a)

(b)

Figure 3. Digitally Adjustable Current Amplifier (DACA): (a) schematic symbol (b) 3rd-order AC simulation model

$$I_{\mathrm{ID}} = I_{\mathrm{IN+}} - I_{\mathrm{IN-}}\ , \tag{3}$$

$$I_{\mathrm{OD}} = I_{\mathrm{OUT+}} - I_{\mathrm{OUT-}}, \quad I_{\mathrm{OD}} = 2AI_{\mathrm{ID}}\ , \tag{4}$$

$$I_{\mathrm{OUT+}} = A(I_{\mathrm{IN+}} - I_{\mathrm{IN-}}), \tag{5}$$

$$I_{\mathrm{OUT-}} = -A(I_{\mathrm{IN+}} - I_{\mathrm{IN-}}). \tag{6}$$

where I_{ID} represents the differential input current, I_{OD} is the differential output current, and A stands for the adjustable current gain of DACA element. It is clear that the differential gain is twice higher than the single-ended gain. A can be adjusted from 1 to 8 in steps of 1.

Measurement results for the DACA features are not yet available; therefore the DACA is modeled only partially and the model does not cover all parameters. Only input and output impedances are modeled, similarly to DO-CF and FD-CF elements.

III. DESIGNED S-E AND F-D FILTER

Universal filter with current-only active elements was designed in both the single-ended (Fig. 4) and the fully-differential (Fig. 5) variant. Independent adjusting of the quality factor for every filtering function is possible by adjustable current gain of DACA in both variants.

The denominator of all transfer functions is for the S-E filter equal to:

$$D(\boldsymbol{s}) = 1 + \boldsymbol{s}C_2R_2A + \boldsymbol{s}^2C_1C_2R_1R_2\ . \tag{7}$$

Provided transfer functions are:

$$\frac{\boldsymbol{I}_{\mathrm{LP}}}{\boldsymbol{I}_{\mathrm{IN}}} = -\frac{\boldsymbol{I}_{\mathrm{iLP}}}{\boldsymbol{I}_{\mathrm{IN}}} = \frac{1}{D(\boldsymbol{s})}\ , \tag{8}$$

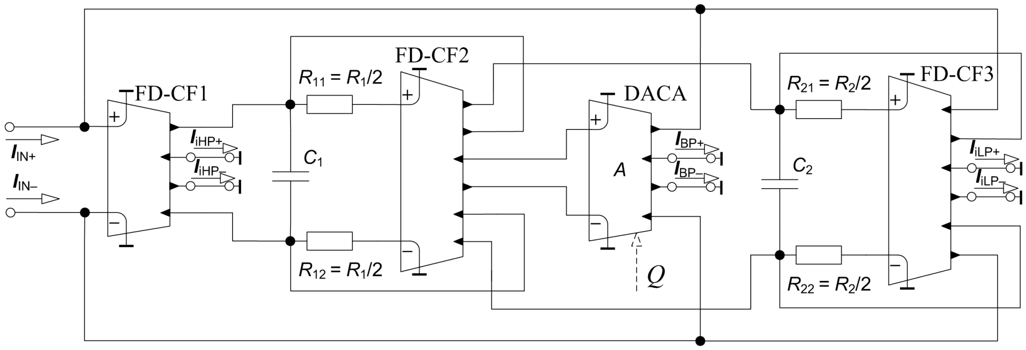


Figure 5. Fully-differential universal and adjustable frequency filter with three FD-CF and one DACA elements working in the current mode

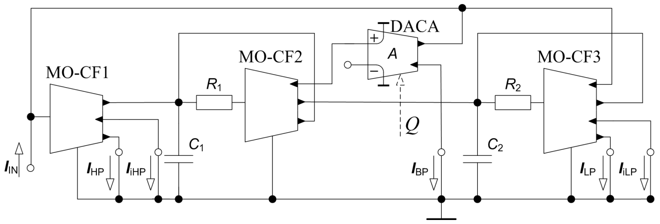


Figure 4. Single-ended universal and adjustable frequency filter with three MO-CF and one DACA elements working in the current mode

$$\frac{\boldsymbol{I}_{\mathrm{BP}}}{\boldsymbol{I}_{\mathrm{VST}}} = \frac{\boldsymbol{s}C_2R_2A}{D(\boldsymbol{s})}\,, \tag{9}$$

$$\frac{\boldsymbol{I}_{\mathrm{HP}}}{\boldsymbol{I}_{\mathrm{IN}}} = -\frac{\boldsymbol{I}_{\mathrm{iHP}}}{\boldsymbol{I}_{\mathrm{IN}}} = \frac{\boldsymbol{s}^2C_1C_2R_1R_2}{D(\boldsymbol{s})}\,, \tag{10}$$

$$\frac{\boldsymbol{I}_{\mathrm{LP}}+\boldsymbol{I}_{\mathrm{HP}}}{\boldsymbol{I}_{\mathrm{IN}}} = -\frac{\boldsymbol{I}_{\mathrm{iLP}}+\boldsymbol{I}_{\mathrm{iHP}}}{\boldsymbol{I}_{\mathrm{IN}}} = \frac{1+\boldsymbol{s}^2C_1C_2R_1R_2}{D(\boldsymbol{s})}\,, \tag{11}$$

$$\frac{\boldsymbol{I}_{\mathrm{iLP}}+\boldsymbol{I}_{\mathrm{BP}}+\boldsymbol{I}_{\mathrm{iHP}}}{\boldsymbol{I}_{\mathrm{IN}}} = -\frac{1-\boldsymbol{s}C_2R_2A+\boldsymbol{s}^2C_1C_2R_1R_2}{D(\boldsymbol{s})}\,. \tag{12}$$

Relations for angular frequency and quality factor can be easily derived:

$$\omega_0 = \sqrt{\frac{1}{R_1R_2C_1C_2}}\,, \tag{13}$$

$$Q = \frac{1}{A}\sqrt{\frac{R_1C_1}{R_2C_2}}\,. \tag{14}$$

It is obvious that the quality factor of filters from Fig. 4 and Fig. 5 can be controlled by DACA gain A with an inverse proportion. The F-D filter is designed so as to have almost the same transfer functions as the S-E filter thanks to appropriately modified values of passive elements as shown in Fig. 5. In order to obtain particular transfer functions for the F-D filter, A in each of the equations has to be replaced by $2A$ because of the differential gain of DACA, which is twice higher than the S-E gain, as demonstrated by eqs. (3)–(6).

Table I
VALUES OF PASSIVE COMPONENTS

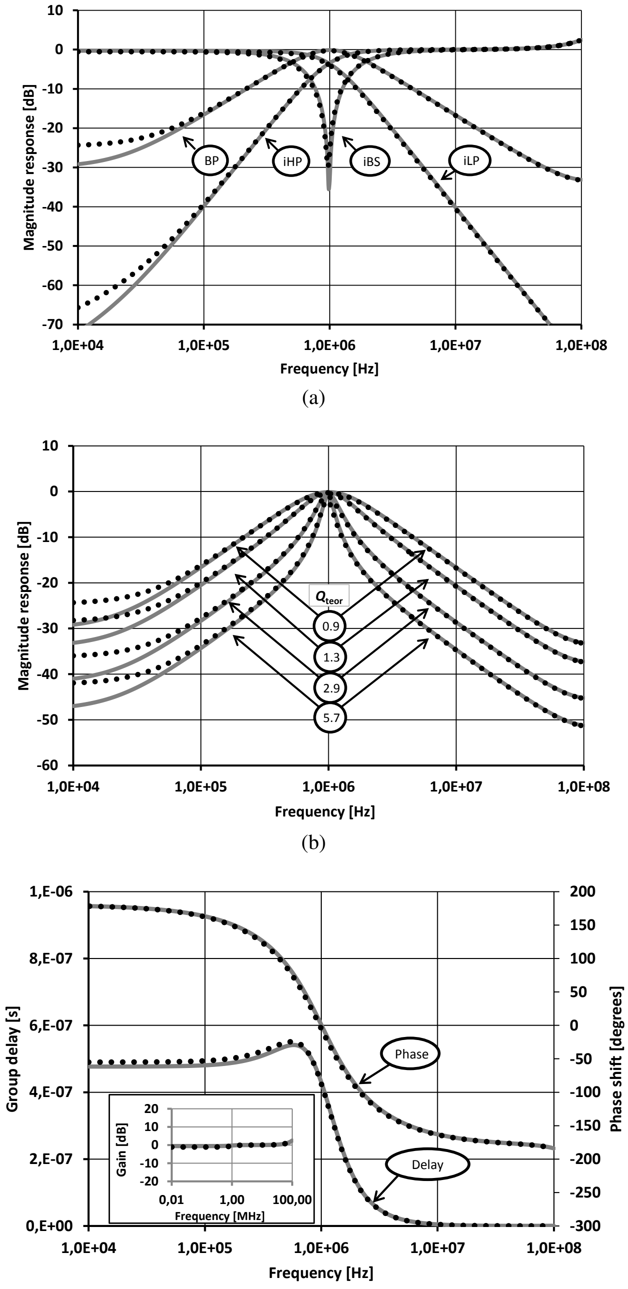
Variant [–]	C_1 [pF]	C_2 [pF]	R_1 [kΩ]	R_2 [Ω]
S-E	430	68	2	390
F-D	430	68	4	200

IV. SIMULATION RESULTS

To verify the theoretical presumptions, the behavior of both the S-E and the F-D filters has been analyzed by Spice simulations. The chosen or calculated values are summarized in Table I. Theoretical pole frequency is 1 MHz in each case, theoretical quality factor is $Q = \{0.9;\ 1.3;\ 2.9;\ 5.7\}$, obtained by gain values $A = \{8;\ 5;\ 2;\ 1\}$. It is clear that resistor values are changed in the case of the F-D filter from Fig. 5, because they are placed in lengthwise branches. Therefore, $R_{11} = R_{12} = 2\ \mathrm{k}\Omega$ and $R_{21} = R_{21} = 100\ \Omega$. Floating capacitor C_1 (and C_2, of course) could be replaced by two grounded capacitors in the particular solution. These capacitors would be 860 pF in the case of C_1 and 136 pF in the case of C_2.

Simulation results comparing the S-E and the F-D filter are shown in Fig. 6. All simulations were done with simple models shown in Fig. 1b, Fig. 2b and Fig. 3b. The graph in Fig. 6a contains magnitude responses of inverting low-pass, band-pass, inverting high-pass and inverting band-stop filters, Fig. 6b shows an example of quality factor adjustment in the case of band-pass filter, and Fig. 6c includes all characteristics of all-pass filter.

The differences between the S-E and the F-D solutions are clearly visible in the low-frequency area, particulary in the case of iHP and BP functions. The F-D filter provides a slightly higher low-frequency attenuation than the S-E solution. In the current mode, low-frequency attenuation is dependent on the output impedances of active elements, but in this particular case, the difference is caused mainly by unequal values of resistors. The theoretical values of the quality factor of BP filters are included in Fig. 6b, the



(a)

(b)

(c)

Figure 6. Simulation results of universal and adjustable filters with four current-only active elements; F-D filter (solid line) compared to S-E filter (dotted line). (a) magnitude response of iLP, iHP, BP and iBS functions (b) adjustement of quality factor in case of BP filter (c) iAP - magnitude and phase response, group delay

simulation results for S-E are 4.3, 2.5, 1.2 and 0.8, and the simulation results for F-D are 4.9, 2.6, 1.2, 0.8.

V. CONCLUSION

Both S-E and F-D filters have several benefits when compared to each other. Simulation results that were shown in this contribution showed that both solutions provide comparable features and therefore both of them can find good applications in communications and transmission systems.

ACKNOWLEDGMENT

This work was supported in part by the Czech Science Foundation, project 102/09/1681 and by the Czech Ministry of Education, program MSM 0021630513.

REFERENCES

[1] O. Casas and R. Pallas-Areny. ”Basics of Analog Differential Filters”, *IEEE Transaction on Instrumentation and Measurement*, Vol. 45, No. 1, pp. 275–279, 1996.

[2] M. O. Shaker, S. A. Mahmoud, and A. M. Soliman, ”New CMOS Fully-Differential Transconductor and Application to a Fully-Differential Gm-C Filter”. *ETRI Journal*, Vol. 28, No. 2, pp. 175–181, 2006.

[3] N. Herencsar, J. Koton, and K. Vrba, ”Differential-Input Buffered and Transconductance Amplifier (DBTA)-Based New Trans-Admittance- and Voltage-Mode First-Order All-Pass Filters”.*In Proceedings of the 6th International Conference on Electrical and Electronics Engineering - ELECO' 09*. Turkey: EMO Yayinlari, pp. 256–259, 2009.

[4] S. A. Mahmoud, ”Low Voltage Fully Differential CMOS Current Feedback Operational Amplifier”, *Proc 47th IEEE Midwest Int Symposium Circuits and Systems*, Vol. 1, pp. 49–52, 2004.

[5] E. A. Soliman and S. A. Mahmoud, ”New CMOS fully differential current conveyor and its application in realizing sixth order complex filter”. *IEEE International Symposium Circuits and Systems*, pp. 57–60, 2009.

[6] E. A. Sobhy and A. M. Soliman, ”Realizations of fully differential voltage second generation current conveyor with an Application”. *International Journal of Circuit Theory and Applications*, Vol. 38, No. 5, pp. 441–452, 2010.

[7] C. M. Chang, B. M. Al-Hashimi, C. L. Wang, and C. W. Hung, ”Single fully differential current conveyor biquad filters”, *IEEE Proc. of Circuits, Devices and Systems*, No. 5, pp. 394–398, 2003.

[8] R. H. Zele, D. J. Allstot, and T. S. Fiez, ”Fully balanced CMOS current-mode circuits”. *IEEE Journal of Solid-State Circuits*, Vol. 28, No. 5, pp. 569–575, 1993.

[9] J. Jerabek, R. Sotner, and K. Vrba, ”Fully-differential current amplifier and its application to universal and adjustable filter”. *In 2010 Int Conf on Applied Electronics*. Pilsen: University of West Bohemia, Czech Republic, pp. 141–144, 2010.

[10] A. Hussain and N. Tasadduq, ”Realizations of CMOS Fully Differential Current Followers/Amplifiers”, *IEEE International Symposium on Circuits and Systems (ISCAS 2009)*, Taipei, Taiwan, pp.1881–1384, 2009.

[11] M. Massarotto, O. Casas, V. Ferrari, and R. Pallas-Areny, ”Improved Fully Differential Analog Filters”. *IEEE Transaction on Instrumentation and Measurement*, Vol. 56, No. 6, pp. 2464–2469, 2007.

[12] W. Tangsrirat and T. Pukkalanun, ”Digitally programmable current follower and its applications,” *Int. J. Electron. Commun. (AEU)*, vol. 63, no. 5, pp. 416–422, 2009.

[13] H. A. Alzaher, ”A CMOS digitally programmable universal current mode filter,” *IEEE Trans. Circuits and Systems II*, vol. 55, no. 8, pp. 758–762, 2008.

[14] B. Sedighi and M. S. Bakhtiar, ”Variable gain current mirror for highspeed appications,” *IEICE Electronics Express*, vol. 4, no. 8, pp. 277–281, 2007.

[15] J. Koton, N. Herencsar, J. Jerabek, and K. Vrba, ”Fully Differential Current-Mode Band-Pass Filter: Two Design Solutions”. *In Proc. 33rd Int Conf on Telecom and Signal Procesing, TSP 2010.* Baden, Austria, pp. 1–4, 2010.

[16] J. Jerabek, K. Vrba, and M. Jelinek, ”Universal Fully-Differential Adjustable Filter with Current Conveyors and Current Amplifier in Comparison with Single-Ended Solution,” *In 2011 Int Conf on Applied Electronics*. Pilsen: University of West Bohemia, Czech Republic, pp. 189–192, 2011.

[17] J. Jerabek, R. Sotner, and K. Vrba, ”Current-Mode Filters with Single-Ended and Fully-Differential Nth- order Synthetic Elements”. *In Proceedings of the 34th International Conference on Telecommunications and Signal Processing TSP 2011*. Budapest: Hungary, pp. 269–273, 2011.

[18] J. Jerabek and K. Vrba, ”Design of Fully-Differential Filters with nth-order Synthetic Elements and Comparison with Single- Ended Solution”. *In Proc of the 2011 Int Conf on Computer and Communication Devices (ICCCD 2011)*. Bali, Indonesia, pp. V1-48 – V1-52, 2011.