Voltage-Mode Universal Filters Employing Single Modified Current Feedback Operational Amplifier (MCFOA)

Norbert Herencsar, Jaroslav Koton, and Kamil Vrba

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

Abstract

This paper deals with the modified current-feedback operational amplifier (MCFOA) that is used in two voltage-mode (VM) frequency filters. Both structures presented employ single active and five passive elements. Circuits enable realizing a low- (LP), band- (BP), and high-pass (HP) filter responses without changing the circuit topology. There is no requirement for additional component or rotation of component to realize band-stop (BS) and all-pass (AP) filter function. Moreover, the independent adjustment of the quality factor Q by varying the value of single passive element without affecting of the natural frequency ω_0 is allowed. All the passive and active sensitivities are low. In the PSPICE simulations the BJT simulation model of the MCFOA and its possible realization using the UCC-N1B 0520 integrated circuit are used to confirm the workability of the proposed circuits.

1. Introduction

In 1968 and 1970, Smith and Sedra introduced the first- (CCI) [1] and second-generation current conveyors (CCII) [2]. The third-generation current conveyor was introduced by Fabre in 1995 [3]. Since then, the CCII became the basic building block of many other active elements. Here, the current-feedback operational amplifier (CFOA) [4], the second-generation current-controlled conveyor (CCCII) [5], the dual-X second-generation current conveyor (DXCCII) [6], the current differencing buffered amplifier (CDBA) [7], or the modified CFOA (MCFOA) [8] can be mentioned. Recently, further research has been focused on current conveyors with variable current and/or voltage gains such as electronically tunable second-generation current conveyor (ECCII) [9], variable gain current conveyor (VGCCII) [10] or voltage and current gain second generation current conveyor (VCG-CCII) [11].

In this paper applications of the modified current-feedback operational amplifier (MCFOA) to voltage-mode universal filters are presented. The two newly proposed filter structures employ single MCFOA as active element and five passive elements. The presented filter topologies enable realizing all standard filter functions. The independent adjustment of the quality factor Q without affecting of the natural frequency ω_0 is also allowed. All the passive and active sensitivities are low. The PSPICE simulation results based on the BJT model of the MCFOA and on the 3rd level model of the UCC-N1B 0520 integrated circuit are included to verify the theoretical analysis of the proposed circuits. The proposed filters can be used in the analog sections of high-speed data communication systems, for signal processing in cable modems, and in other applications.

2. Modified Current-Feedback Operational Amplifier

The modified current-feedback operational amplifier (MCFOA) [8] is a combination of the plus-type (CCII+) and minus-type (CCII−) of second-generation current conveyor [2] and its schematic symbol is shown in Fig. 1. Relations between the individual terminals of the MCFOA can be described as follows:

$$i_Z = i_X, \quad i_Y = -i_W, \quad v_X = v_Y, \quad v_W = v_Z. \qquad (1)$$

As it can be seen from (1), the MCFOA is different from the conventional current-feedback operational amplifier (CFOA) used in [4], because the W terminal current of the MCFOA is copied to the Y terminal in the opposite direction. However, it is well known that the Y-terminal current of the conventional CFOA is equal to zero [8]. In fact, the MCFOA presented in [8] is the composite current conveyor (CCC) introduced by Smith and Sedra in [12]. That can be also seen after comparison of both sets of circuit equations in [8] and [12].

In 2000, the Universal Current Conveyor (UCC) [13-16] was designed and developed, using the CMOS 0.35 μm technology, under the designation UCC-N1B 0520 at our workplace, and produced in cooperation with AMI Semiconductor Czech, Ltd., (now ON Semiconductor Czech Republic, Ltd.). The UCC is defined as an eight-port active element and its schematic symbol is shown in Fig. 2a. Analogous to differential difference current conveyor (DDCC) [17] or to differential difference complementary current conveyor (DDCCC) [18], the UCC has three high-impedance voltage inputs (Y1+, Y2−, Y3+) (one differencing - Y2−, and two additive - Y1+, Y3+), one low impedance input X, and four current outputs (Z1+, Z1−, Z2+, Z2−). Outputs Z1− and Z2− are inverse to outputs Z1+, Z2+. By connecting or grounding suitable terminals of the UCC, it helps to realize all existing types of current conveyors with single low impedance input X such as CCI+, CCI−, CCI+/−, CCII+, CCII−, CCII+/−, CCIII+, CCIII−, CCIII+/−, inverting-types of current conveyors such as ICCI+, ICCI−, ICCI+/−, ICCII+, ICCII−, ICCII+/−, ICCIII+, ICCIII−, ICCIII+/−, and other types with

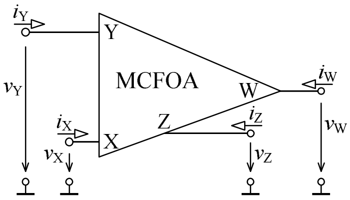


Fig. 1. Schematic symbol of the MCFOA

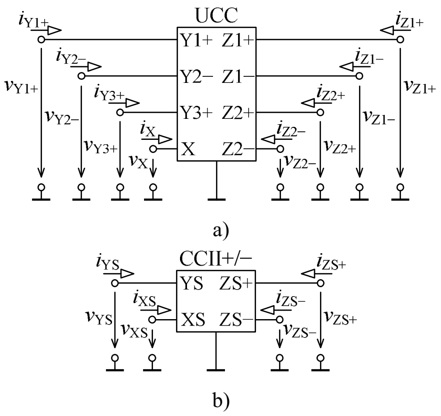


Fig. 2. a) The UCC and b) CCII+/− elements in the UCC-N1B 0520 integrated circuit

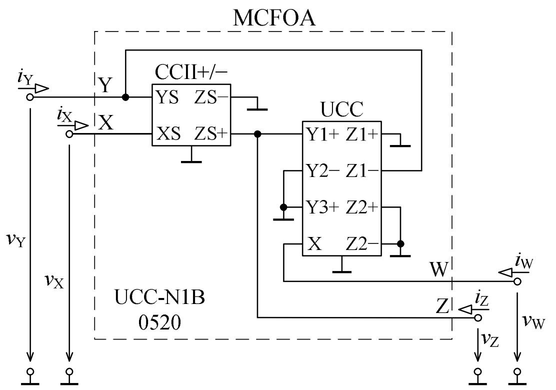


Fig. 3. Possible realization of the MCFOA by UCC-N1B 0520 device

differential input such as DVCCI+, DVCC−, DVCC+/−, DVCCI−, DVCCIII+, DDCC+, DDCC−, and DDCC+/−. The implementation method of current conveyors mentioned above was introduced by Becvar *et al*. [13]. In addition to UCC, the UCC-N1B 0520 integrated circuit also includes the CCII+/− [2], as shown in Fig. 2b. The relationship between port currents and voltages of the UCC can be described as follows:

$$v_{X} = v_{Y1+} - v_{Y2-} + v_{Y3+}, \tag{2a}$$

$$i_{Y1+} = i_{Y2-} = i_{Y3+} = 0, \tag{2b}$$

$$i_{Z1+} = i_{Z2+} = i_{X}, \quad i_{Z1-} = i_{Z2-} = -i_{X}, \tag{2c}$$

and the second-generation current conveyor CCII+/− can be described by the following equations:

$$v_{XS} = v_{YS}, \tag{3a}$$

$$i_{YS} = 0, \tag{3b}$$

$$i_{ZS+} = i_{XS}, \quad i_{ZS-} = -i_{XS}. \tag{3c}$$

The UCC-N1B 0520 integrated circuit is that universal we could use it for the implementation of MCFOA. The realization of the MCFOA by UCC-N1B 0520 device is shown in Fig. 3 [19]. Other possible realizations of the MCFOA using CMOS or commercially available amplifier AD844 can be found in [8].

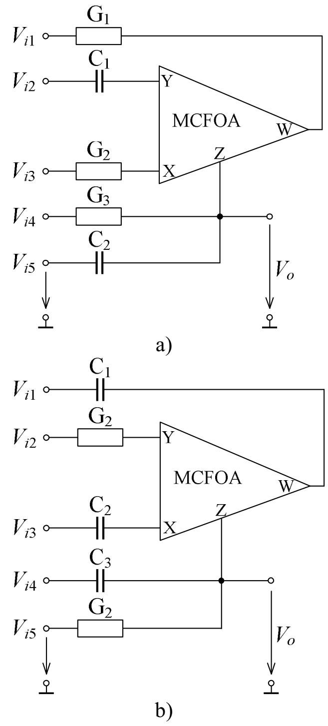


Fig. 4. Proposed voltage-mode universal filter topologies employing single MCFOA

3. Proposed Filters Employing Single MCFOA

The proposed voltage-mode (VM) universal filters in Fig. 4 require the minimum number of active and passive elements. However, the passive elements are floating and the proposed filter topologies might be not attractive for integration [20]. Anyway, it should be mentioned that unused voltage inputs are always grounded, as described later. The output voltage V_o of the circuit topology in Fig. 4a is given by the relation as follows:

$$V_o = \frac{G_1G_2V_{i1} + sC_1G_2V_{i2} - sC_1G_2V_{i3} + sC_1G_3V_{i4} + s^2C_1C_2V_{i5}}{s^2C_1C_2 + sC_1G_3 + G_1G_2}. \tag{4}$$

For the proposed filter depending on the status of circuit input five voltages V_{i1}, V_{i2}, V_{i3}, V_{i4} and V_{i5} numerous filter functions are obtained. From (4), we can see that:

(i) If $V_{i2} = V_{i3} = V_{i4} = V_{i5} = 0$ (grounded), a low-pass filter (LP) can be obtained with V_o/V_{i1};
(ii) If $V_{i1} = V_{i3} = V_{i4} = V_{i5} = 0$ (grounded), a band-pass filter (BP1) can be obtained with V_o/V_{i2};
(iii) If $V_{i1} = V_{i2} = V_{i4} = V_{i5} = 0$ (grounded), a band-pass filter (BP2) can be obtained with V_o/V_{i3};
(iv) If $V_{i1} = V_{i2} = V_{i3} = V_{i5} = 0$ (grounded), a band-pass filter (BP3) can be obtained with V_o/V_{i4};
(v) If $V_{i1} = V_{i2} = V_{i3} = V_{i4} = 0$ (grounded), a high-pass filter (HP) can be obtained with V_o/V_{i5};
(vi) If $V_{i2} = V_{i3} = V_{i4} = 0$ (grounded) and $V_{i1} = V_{i5} = V_{in}$, a band-stop filter (BS) can be obtained with V_o/V_{in};
(vii) If $V_{i2} = V_{i4} = 0$ (grounded), $V_{i1} = V_{i3} = V_{i5} = V_{in}$, and $G_2 = G_3$ an all-pass filter (AP) can be obtained with V_o/V_{in}.

Thus, the circuit is capable of realizing all standard filter functions such as low- (LP), band- (BP), high-pass (HP), band-stop (BS), and all-pass (AP) response without changing the circuit topology.

For all filters the natural frequency ω_0, quality factor Q and bandwidth BW derived from the denominator of (4) are:

$$\omega_0 = \sqrt{\frac{G_1 G_2}{C_1 C_2}}, \tag{5a}$$

$$Q = \frac{1}{G_3}\sqrt{\frac{C_2 G_1 G_2}{C_1}}, \tag{5b}$$

$$\mathrm{BW} = \frac{\omega_0}{Q} = \frac{G_3}{C_2}. \tag{5c}$$

Note that, the quality factor Q (5b) of the proposed filter in Fig. 4a can be controlled independently of natural frequency ω_0 (5a) by varying G_3. By replacing appropriate conductor by FET-based voltage-controlled resistor (VCR) [21] the quality factor Q can be controlled electronically that is a particular advantage of the proposed circuit. The natural frequency ω_0 (5a) can be independently adjusted from the bandwidth (5c), by varying C_1, G_1 or G_2 of the proposed frequency filter.

Taking into account the non-ideal MCFOA [8], namely $i_Z = \alpha_1 i_X$, $i_Y = -\alpha_2 i_W$, $v_X = \beta_1 v_Y$, and $v_W = \beta_2 v_Z$, where $\alpha_1 = 1 - \varepsilon_{i1}$, $\alpha_2 = 1 - \varepsilon_{i2}$ and ε_{i1}, ε_{i2} ($|\varepsilon_{i1}|, |\varepsilon_{i2}| \ll 1$) denote the current tracking errors, $\beta_1 = 1 - \varepsilon_{v1}$, $\beta_2 = 1 - \varepsilon_{v2}$ and ε_{v1}, ε_{v2} ($|\varepsilon_{v1}|, |\varepsilon_{v2}| \ll 1$) are the voltage tracking errors of MCFOA, respectively. The denominator of (4) becomes:

$$D_1(s) = s^2 C_1 C_2 + s C_1 G_3 + \alpha_1 \alpha_2 \beta_1 \beta_2 G_1 G_2. \tag{6}$$

The natural frequency ω_0, quality factor Q and bandwidth BW from (6) can be rewritten as:

$$\omega_0 = \sqrt{\alpha_1 \alpha_2 \beta_1 \beta_2 \frac{G_1 G_2}{C_1 C_2}}, \tag{7a}$$

$$Q = \frac{1}{G_3}\sqrt{\alpha_1 \alpha_2 \beta_1 \beta_2 \frac{C_2 G_1 G_2}{C_1}}, \tag{7b}$$

$$\mathrm{BW} = \frac{\omega_0}{Q} = \frac{G_3}{C_2}. \tag{7c}$$

The active and passive sensitivities of the proposed VM universal filter topology in Fig. 4a derived from (7a)-(7c) are as follows:

$$S^{\omega_0}_{\alpha_1,\alpha_2,\beta_1,\beta_2,G_1,G_2} = -S^{\omega_0}_{C_1,C_2} = \frac{1}{2}, \quad S^{\omega_0}_{G_3} = 0, \tag{8a}$$

$$S^{Q}_{\alpha_1,\alpha_2,\beta_1,\beta_2,C_2,G_1,G_2} = -S^{Q}_{C_1} = \frac{1}{2}, \quad S^{Q}_{G_3} = -1, \tag{8b}$$

$$S^{\mathrm{BW}}_{G_3} = -S^{\mathrm{BW}}_{C_2} = 1, \quad S^{\mathrm{BW}}_{\alpha_1,\alpha_2,\beta_1,\beta_2,C_1,G_1,G_2} = 0. \tag{8c}$$

From the results it is evident that the sensitivities are low and not larger than unity in absolute value.

By simple RC:CR transformation of the circuit of Fig. 4a, in this paper we present another one VM universal filter topology employing single MCFOA and five passive elements. Routine analysis of the proposed filter topology in Fig. 4b yields the following voltage transfer functions:

$$K_{\mathrm{V\_HP}} = \frac{V_o}{V_{i1}} = \frac{s^2 C_1 C_2}{D_2(s)}, \quad K_{\mathrm{V\_BP1}} = \frac{V_o}{V_{i2}} = \frac{s C_2 G_1}{D_2(s)}, \tag{9a,b}$$

$$K_{\mathrm{V\_BP2}} = \frac{V_o}{V_{i3}} = -\frac{s C_2 G_1}{D_2(s)}, \quad K_{\mathrm{V\_BP3}} = \frac{V_o}{V_{i4}} = \frac{s C_3 G_1}{D_2(s)}, \tag{9c,d}$$

$$K_{\mathrm{V\_LP}} = \frac{V_o}{V_{i5}} = \frac{G_1 G_2}{D_2(s)}, \tag{9e}$$

$$K_{\mathrm{V\_BS}} = \frac{V_o}{V_{i1} + V_{i5}} = \frac{s^2 C_1 C_2 + G_1 G_2}{D_2(s)}, \tag{9f}$$

$$K_{\mathrm{V\_AP}} = \frac{V_o}{V_{i1} + V_{i3} + V_{i5}} = \frac{s^2 C_1 C_2 - s C_2 G_1 + G_1 G_2}{D_2(s)}, \tag{9g}$$

where

$$D_2(s) = s^2 C_1 C_2 + s C_3 G_1 + G_1 G_2. \tag{10}$$

As seen from (9a)-(9g), the proposed filter in Fig. 4b is capable of realizing all standard filter functions mentioned above. For all filters the natural frequency ω_0, quality factor Q and bandwidth BW derived from (10) are:

$$\omega_0 = \sqrt{\frac{G_1 G_2}{C_1 C_2}}, \tag{11a}$$

$$Q = \frac{1}{C_3}\sqrt{\frac{C_1 C_2 G_2}{G_1}}, \tag{11b}$$

$$\mathrm{BW} = \frac{\omega_0}{Q} = \frac{C_3 G_1}{C_1 C_2}. \tag{11c}$$

The quality factor Q (11b) of the proposed filters can be controlled independently of natural frequency ω_0 (11a) by varying C_3. By replacing appropriate capacitor by voltage-controlled capacitor (VCC) designed using a current-controlled voltage source (CCVS) and a current-controlled current source (CCCS) [22] or by digitally-controlled varactor (DCV) [23] the quality factor Q can be controlled electronically, which is advantage of the proposed circuit. The natural frequency ω_0 (11a) can be independently adjusted from the bandwidth (11c), by varying G_2 of the proposed frequency filter.

Taking into account the non-ideal MCFOA discussed above, the denominator (10) of the transfer functions (9a)-(9g) becomes:

$$D_2(s) = s^2 \alpha_1 \alpha_2 \beta_1 \beta_2 C_1 C_2 + s C_3 G_1 + G_1 G_2. \tag{12}$$

and the natural frequency ω_0, quality factor Q and bandwidth BW can be rewritten as:

$$\omega_0 = \sqrt{\frac{G_1 G_2}{\alpha_1 \alpha_2 \beta_1 \beta_2 C_1 C_2}}, \tag{13a}$$

$$Q = \frac{1}{C_3}\sqrt{\alpha_1 \alpha_2 \beta_1 \beta_2 \frac{C_1 C_2 G_2}{G_1}}, \tag{13b}$$

$$\mathrm{BW} = \frac{\omega_0}{Q} = \frac{C_3 G_1}{\alpha_1 \alpha_2 \beta_1 \beta_2 C_1 C_2}. \tag{13c}$$

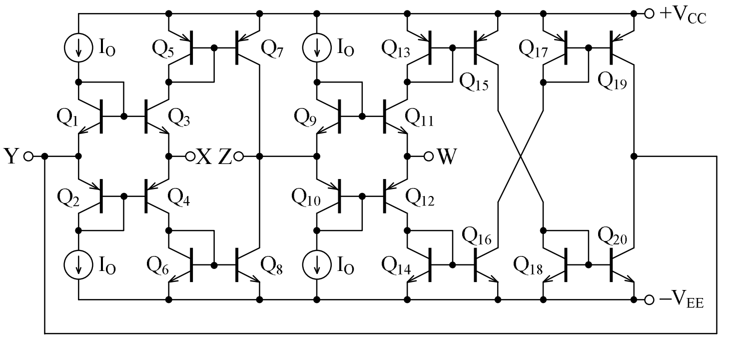


Fig. 5. Bipolar implementation of MCFOA

The active and passive sensitivities of the proposed VM universal filter topology in Fig. 4b derived from (13a)-(13c) are as follows:

$$S^{\omega_0}_{G_1,G_2} = -S^{\omega_0}_{\alpha_1,\alpha_2,\beta_1,\beta_2,C_1,C_2} = \frac{1}{2}, \quad S^{\omega_0}_{C_3} = 0, \qquad (14a)$$

$$S^{Q}_{\alpha_1,\alpha_2,\beta_1,\beta_2,C_1,C_2,G_2} = -S^{Q}_{G_1} = \frac{1}{2}, \quad S^{Q}_{C_3} = -1, \qquad (14b)$$

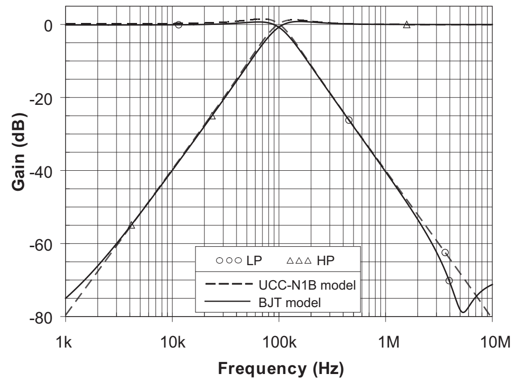
$$S^{\mathrm{BW}}_{C_3,G_1} = -S^{\mathrm{BW}}_{\alpha_1,\alpha_2,\beta_1,\beta_2,C_1,C_2} = 1, \quad S^{\mathrm{BW}}_{G_2} = 0. \qquad (14c)$$

From the results it is evident that the sensitivities are again low and not larger than unity in absolute value.

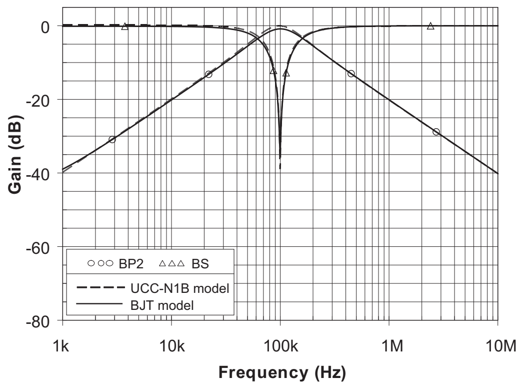
4. Simulation Results

The behavior of the proposed VM universal filter topology in Fig. 4a has been verified by PSPICE simulations. Used internal BJT structure of the MCFOA is shown in Fig. 5. The CCII+ is formed by transistors $Q_1 - Q_8$ and transistors $Q_9 - Q_{20}$ represent a CCII−. In the design the transistor model parameters NR100N (NPN) and PR100N (PNP) of bipolar arrays ALA400 from AT&T [24] were used. Supply voltages of $+V_{CC} = -V_{EE} = 2.5$ V and the bias current $I_O = 200$ μA have been chosen.

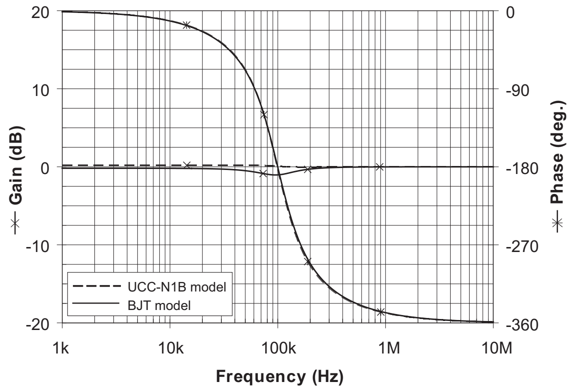
The behavior of the filter in Fig. 4a has also been simulated by PSPICE software using model shown in Fig. 3. In the simulations the 3rd level model [25] of the UCC-N1B 0520 device has been used, which is based on the measurement of the fabricated fifty laboratory prototypes. In this paper the BJT realization of the MCFOA is the primary internal structure. Simulations using the real model of the UCC-N1B 0520 help more to verify and confirm the workability of the proposed circuit. For the characteristic frequency $f_0 = \omega_0/2\pi \cong 100$ kHz and the quality factor of filters $Q = 1$ the following passive component values have been chosen: $C_1 = C_2 = 1.5$ nF and $G_1 = G_2 = G_3 = 1$ mS ($R_1 = R_2 = R_3 = 1$ kΩ). The simulation results of the low- (LP), band- (BP2), high-pass (HP), band-stop (BS) and all-pass (AP) filter working in voltage mode are shown in Fig. 6. For the band-pass filter response BP3, the independent adjustment of the quality factor Q by varying the value of G_2 without affecting of the natural frequency ω_0 is shown in Fig. 7. Here, for chosen values $Q = \{0.3;\ 1;\ 3;\ 10;\ 30\}$ the conductivity must be $G_3 = \{3.333;\ 1.000;\ 0.333;\ 0.100;\ 0.033\}$ mS ($R_3 = \{0.3;\ 1;\ 3;\ 10;\ 30\}$ kΩ). The PSPICE simulations confirm the feasibility of the proposed circuit. From the simulation results it is also evident that the final solution corresponds to the theory and both the MCFOA realizations are almost equivalent.



a)



b)



c)

Fig. 6. Simulated frequency characteristics for (a) LP and HP, (b) BP2 and BS, (c) AP responses of the circuit in Fig. 4a

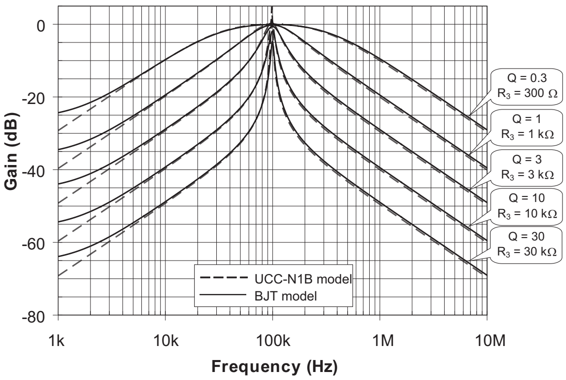


Fig. 7. Simulation results of proposed VM band-pass filter BP3 for the values of quality factor $Q = \{0.3; 1; 3; 10; 30\}$

5. Conclusions

In this paper new voltage-mode universal frequency filter topologies employing single MCFOA and five passive elements are presented. The independent control of the quality factor Q using single passive element is possible, which can be advantageous in some applications. The behavior of the proposed VM filter has been verified by PSPICE simulations. In simulations the bipolar structure and the 3rd level model of the UCC-N1B 0520 device have been used to implement the MCFOA. From simulation results it is evident that the final solutions correspond to theory.

6. Acknowledgment

The paper has been supported by the Czech Science Foundation project GACR 102/09/1681 and Ministry of Education of the Czech Republic project No. MSM0021630513.

7. References

[1] K. C. Smith and A. Sedra, "The current conveyor: A new circuit building block", *IEEE Proc.*, vol. 56, pp. 1368-1369, 1968.

[2] A. Sedra and K. C. Smith, "A second generation current conveyor and its applications", *IEEE Trans. Circ. Theory*, vol. 17, pp. 132-134, 1970.

[3] A. Fabre, "Third generation current conveyor: a new helpful active element", *Electron. Lett.*, vol. 31, pp. 338-339, 1995.

[4] J. A. Svoboda, L. McGory, and S. Webb, "Applications of a commercially available current conveyor", *Int. J. Electronics*, vol. 70, pp. 159-164, 1991.

[5] A. Fabre, O. Saaid, F. Wiest, and C. Boucheron, "High frequency applications based on a new current controlled conveyor", *IEEE Trans. Circuits and Systems–I*, vol. 43, pp. 82-91, 1996.

[6] A. Zeki and A. Toker, A, "The dual-X current conveyor (DXCCII): a new active device for tunable continuous-time filters", *Int. J. Electronics*, vol. 89, pp. 913-923, 2002.

[7] C. Acar and S. Ozoguz, "A new versatile building block: current differencing buffered amplifier suitable for analog signal processing filters", *Microelectronics Journal*, vol. 30, pp. 157-160, 1999.

[8] E. Yuce and S. Minaei, "A modified CFOA and its applications to simulated inductors, capacitance multipliers, and analog filters", *IEEE Trans. Circuits and Systems–I*, vol. 55, pp. 266-275, 2008.

[9] S. Minaei, O. K. Sayin, and H. Kuntman, "A new CMOS electronically tunable current conveyor and its application to current-mode filters", *IEEE Trans. Circuits and Systems–I*, vol. 53, pp. 1448-1457, 2006.

[10] E. Yuce, K. Pal, and S. Minaei, "A high input impedance voltage-mode all-pass/notch filter using a single variable gain current conveyor", *J. Circuits, Systems, and Computers*, vol. 17, pp. 827-834, 2008.

[11] A. De Marcellis, G. Ferri, N. C. Guerrini, G. Scotti, V. Stornelli, and A. Trifiletti, "The VCG-CCII: a novel building block and its application to capacitance multiplication", *Analog Integrated Circuits and Signal Processing*, vol. 58, pp. 55-59, 2009.

[12] K. C. Smith and A. S. Sedra, "Realization of the Chua family of new nonlinear network elements using the current conveyor", *IEEE Trans. Circ. Theory*, vol. 17, pp. 137-139, 1970.

[13] D. Becvar, K. Vrba, V. Zeman, and V. Musil, "Novel universal active block: A Universal Current Conveyor", in *Proc. of the IEEE Int. Symposium on Circuits and Systems - ISCAS'00*, Geneva, Switzerland, 2000, pp. 471-474.

[14] J. Cajka, K. Vrba and J. Misurec, "New universal biquad using UCCX devices", *Frequenz*, vol. 60, pp. 138–141, 2006.

[15] N. Herencsar and K. Vrba, "Current conveyors-based circuits using novel transformation method", *IEICE Electronics Express*, vol. 4, pp. 650-656, 2007.

[16] J. Jerabek and K. Vrba, "SIMO type low-input and high-output impedance current-mode universal filter employing three universal current conveyors", *Int. J. Electron. Commun. (AEU)*, article in press, 2009.

[17] W. Chiu, S. I. Liu, H. W. Tsao and J. J. Chen, "CMOS differential difference current conveyors and their applications", *IEE Proc.-Circuits Devices Syst.*, vol. 144, pp. 91-96, 1996.

[18] S. S. Gupta and R. Senani, Comment on "CMOS differential difference current conveyors and their applications", *IEE Proc.-Circuits Devices Syst.*, vol. 148, pp. 335-336, 2001.

[19] N. Herencsar, J. Koton, K. Vrba, and O. Cicekoglu, "Single UCC-N1B 0520 device as a modified CFOA and its application to voltage- and current-mode universal filters", in *Proc. of the Int. Conference Applied Electronics - APPEL'09*, Pilsen, Czech Republic, 2009, pp. 127-130.

[20] M. Bhusan and R. W. Newcomb, "Grounding of capacitors in integrated circuits", *Electron. Lett.*, vol. 3, pp. 148-149, 1967.

[21] R. Senani, "Realisation of linear voltage-controlled-resistance in floating form", *Electron. Lett.*, vol. 30, pp. 1909-1911, 1994.

[22] R. W. Newcomb, "The semistate description of nonlinear time-variable circuits", *IEEE Trans. Circuits and Systems*, vol. 28, pp. 62-71, 1981.

[23] P. L. Chen, C. C. Chung, and C. Y. Lee, "A portable digitally controlled oscillator using novel varactors", *IEEE Trans. Circuits and Systems–II*, vol. 52, pp. 233-237, 2005.

[24] D. R. Frey, "Log-domain filtering: an approach to current-mode filtering", *IEE Proc. G*, vol. 140, pp. 406-416, 1993.

[25] R. Sponar and K. Vrba, "Measurements and behavioural modelling of modern conveyors", *IJCSNS Int. J. of Comp. Science and Network Security*, vol. 6, pp. 57-65, 2006.