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Current-Mode Circuits Based on SIMO OTA:

Review and New Applications in Filters

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Abstract

The paper deals with design of low-order RC filters working in current mode (CM). As the basic building blocks, transconductors (OTA) with single input and multiple outputs are used. One-loop, two-loop and multi-loop structures are discussed. The adjoint VM-CM transformation is used to obtain new circuits from known VM prototype. The designed structures are verified by Pspice simulations using models of OTAs on transistor level of description.

Keywords: Analogue circuits, active RC filters, transconductors, current mode

1 Introduction

Classical active RC filters [1] based on the voltage mode operational amplifiers are widely used in many low frequency applications. However at higher frequencies, usability of operational amplifiers is limited. More suitable active blocks for higher frequencies are for example transconductors (OTA-s) [1] or its derivatives such as current differencing transconductance amplifiers (CDTAs) [18]. These components have following attractive features:

- higher speed of the signal processing, operation at the higher frequencies (several MHz),
- implementation in full integration form using modern bipolar, CMOS, BiCMOS and GaAs technologies,
- the transconductance parameter (g_m) can be electronically controlled by DC current I_{SET}, what gives us the possibility of electronic tuning.

However, the transconductors have also some disadvantages. Important problem is low dynamic range of input voltage. There is possibility of using a linearization technique which increases the dynamic range.

The OTA based circuits have been widely researched in recent years ([1]-[9]). These circuits work mainly in the voltage mode (VM), where the OTA-DISO active blocks (differential-input single-output) are usually used. These VM structures are based on voltage amplifiers (multipliers by constant), voltage integrators and voltage feedback. Some current mode circuits (filters) were published too, for example multi-output OTAs are used in KHN filter in reference [11].

Progress in signal processing has shown that current mode (CM) approach is better than the VM in terms of its wider bandwidth, higher speed, lower DC voltage and power biasing, larger dynamic range and simplicity in circuit implementation.

The CM network can be obtained by direct synthesis or from the VM prototype using the adjoint VM → CM transformation [2], what will be detailed discussed below. Note that the CM circuit can be based on the same building blocks like the VM but for the current signal processing. The basic building block of CM structures is the current integrator. These CM blocks have different circuit topology and different active components are used. In the case of the OTA, instead of the DISO type, using single-input multiple-output (SIMO) type is more suitable.

2 Transconductor with single input and multiple outputs

The symbol of OTA-SIMO is shown in Fig. 1a. Ideal OTA-SIMO is voltage-controlled current source with single input and multiple outputs. Its operation is described by following equations

$$I_{o1} = \pm I_{o2} = \ldots = \pm I_{on} = g_m \cdot V_i, \quad Z_i = Z_o = \infty \,. \tag{1}$$

The transconductance (g_m) can be controlled externally by DC current I_{SET}, what gives us possibility of electronic control of parameters of OTA based circuits. Note that linear relationship between g and I_{SET} is typical for CMOS implementation operating in weak inversion area. But it is not truth for saturation area where the relationship between g and I_{SET} is quadratic. Typical values of g are in the range of tens to hundreds of μS for CMOS technology (up to some mS for BJT). Input resistance of real OTA is very high, from hundreds of kΩ to tens of MΩ. However the output resistance is smaller (in the range 50 kΩ - 1 MΩ).

Parasitic capacitances are very small (units of pF). Maximal working frequency of these active blocks is several hundreds MHz. For very high frequencies, relationship between the parameter g and frequency is appearing.

$$g(s) = \frac{g_m}{1 + s\tau_g} \cdot \qquad (2)$$

The linearization technique makes the OTA able to handle input signal of the order of volts.

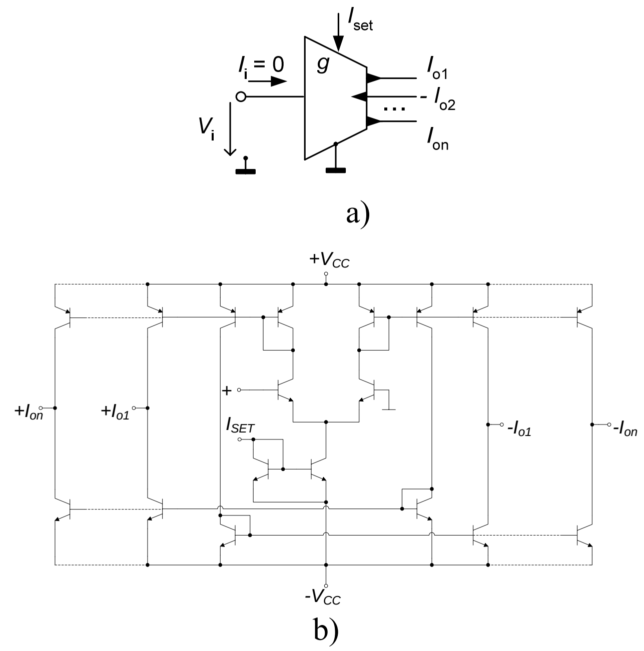

Fig. 1. Transconductor OTA-SIMO.
a) Symbol, b) circuit diagram.

At first sight, the idea of single input OTA gives us the possibility of simpler circuit structure without standard differential stage at the input. However considering technology aspect of this, it is better to use the well-known structure of the input stage adopted from [10]. The circuit was little modified. Inverting input (V-) was grounded. There is also possibility of adjusting of the transconductance of OTA (g_m) by varying control current I_{SET}. Furthermore for obtaining other current replicas $\pm I_o$ with opposite phases, more current mirrors were added to input stage. The resulting circuit diagram for BJT technology is shown in Fig. 1b. Similar circuit for the CMOS technology was given in [11].

3 Zero-order OTA-SIMO CM circuits

Firstly, let's summarize all OTA-SIMO building blocks necessary for realization circuits in the CM. The basic zero-order building block is *current distributor* (Fig. 2a), which producing *n* current replicas (I_{on}) of the input current (I_i). Current gain of this block is exactly one. Note that at input port this circuit can also emulate grounded resistor $Z_i = 1/g_m$. Floating resistor emulation requires two OTAs.

Adding a resistor at the input (Fig. 2b), attenuator is obtained. The current transfer function is

$$K_i = \frac{g_m}{g_m + G} < 1 \cdot \tag{3}$$

Removing the negative feedback, multi-output *current amplifier* or *multiplier* by constant is obtained (Fig. 2c). The gain is

$$K_i = (\pm)\frac{g_m}{G} \cdot \tag{4}$$

This circuit can be also used as weighted current distributor. It can be modified for integrated circuit realization as shown in Fig. 2d.

Note that *current summer* can be realized very easy by only single node connection what comes from current Kirchhof law. This is one of advantages of the current mode.

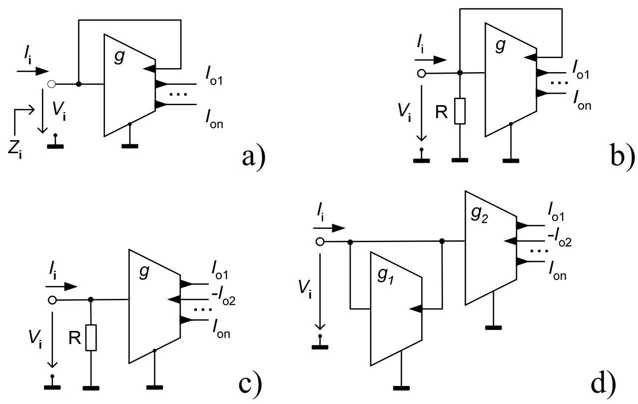

Fig. 2. Zero order CM circuit with OTA-SIMO.
a) Current distributor, b) current anttenuator, c) current amplifier, d) modification for IC form.

4 OTA-SIMO current integrators

Basic first-order building block, especially for the CM filters, is the *current integrator*. Two circuit diagrams of this block based on the OTA-SIMO are shown in Fig. 3. The ideal (lossless) integrator in Fig. 3a has simple current transfer function

$$K(s) = \frac{1}{s\tau}, \quad \tau = g^{-1}C \cdot \tag{5}$$

The lossy integrator in Fig. 3b has transfer function

$$K(s)=\frac{g_m}{sC+g_m}=\frac{1}{1+s\tau},\quad \tau=g_m^{-1}C, \tag{6}$$

transfer function of its modification in Fig. 3c is

$$K(s)=\frac{g_m}{sC+g_m+G}. \tag{7}$$

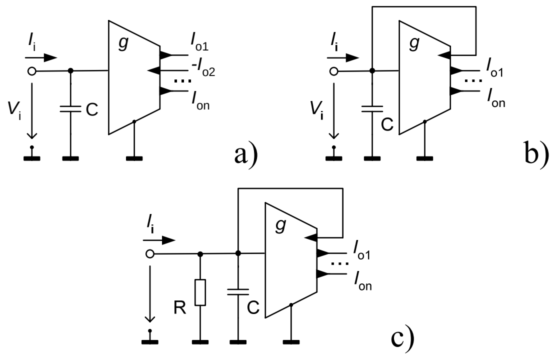

Fig. 3. Current integrators with OTA-SIMO.
a) Ideal integrator, b) c) lossy integrator.

5 Example of feedback loop structures with OTA in CM

The circuit given above (Fig. 3c) can be generalized by the model in Fig. 4. It consists of the single OTA-SIMO, three admittances and one loop of current feedback (I_{FB}). Note that similar model with five admittances was firstly published in [15] and discussed in [3]. However the simpler model in Fig. 4 is suitable for our application. Using adjoint transformation, voltage mode circuit discussed in [14] can be obtained. In [14] systematic design procedure of these circuits based on the autonomous networks with the single OTA-DISO and voltage feedback was described and several appropriate circuits were presented and studied.

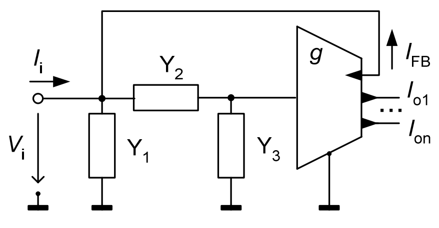

Fig. 4. General CM model with one OTA-SIMO and three admittances.

The general circuit in Fig. 4 was symbolically analyzed using program SNAP. The resulting current transfer function can be written in general symbolic formula

$$K(s) = \frac{I_o}{I_i} = \frac{g_m Y_2}{Y_1 Y_2 + Y_1 Y_3 + Y_2 Y_3 + g_m Y_2} \cdot \tag{8}$$

5.1 OTA first-order circuits

For the first-order circuits, one capacitor and two resistors can be chosen. Choosing Y_1 = sC_1, $Y_2 = G_2$, $Y_3 = G_3$, the circuit realizes low pass (LP) filter with the following transfer function

$$K(s) = \frac{g_m G_2}{sC_1(G_2 + G_3) + G_2(G_3 + g_m)} \cdot \tag{9}$$

Another LP structure can be obtained if $Y_1 = G_1$, $Y_2 = G_2$, Y_3 = sC_3. The high pass filter (HP) is realized for setting $Y_1 = G_1$, Y_2 = sC_2 and $Y_3 = G_3$. Then the general transfer function (8) is transformed to

$$K(s) = \frac{sC_2 g_m}{sC_2(G_1 + G_3 + g_m) + G_1 G_3} \cdot \tag{10}$$

5.2 Second-order CM circuits with single OTA

The general structure based on single OTA-SIMO (Fig. 4) can be also used for the second order CM circuits. The simplest second order LP is obtained by setting Y_1 = sC_1, $Y_2 = G_2$, Y_3 = sC_3, the resulting current transfer function is

$$K(s) = \frac{g_m G_2}{s^2 C_1 C_3 + s(C_1 + C_3)G_2 + g_m G_2} \cdot \tag{11}$$

Comparing (11) with the standard form (12)

$$K(s) = \frac{K_0 \omega_C^2}{s^2 + s\dfrac{\omega_C}{Q} + \omega_C^2}, \tag{12}$$

Formulas for cut-off frequency and quality factor of frequency filter are

$$\omega_C = \sqrt{\frac{g_m G_2}{C_1 C_3}}, \quad Q = \sqrt{\frac{g_m}{G_2}} \frac{\sqrt{C_1 C_3}}{C_1 + C_3}, \tag{13}$$

For simplification of the design and for decreasing of values of sensitivities, we set $C_1 = C_3 = C$. Formulas for values of the other components are very simple

$$G_2 = \frac{C\omega_C}{2Q}, \quad g_m = 2QC\omega_C \cdot \tag{14}$$

Sensitivities of the filter are extremely low

$$S_{g_m}^{\omega p} = S_{G2}^{\omega p} = -S_{C1}^{\omega p} = -S_{C3}^{\omega p} = S_{g_m}^{Q} = -S_{G2}^{Q} = 0{,}5, \quad -S_{C1}^{Q} = S_{C3}^{Q} = 0{,}5\frac{C_1 - C_3}{C_1 + C_3} = 0 \cdot \tag{15}$$

A modified circuit can be obtained if another resistor is added parallel to the first capacitor. Then Y_1 = sC_1+ G_1, Y_2 = G_2, Y_3 = sC_3, and the current transfer function is

$$K(s) = \frac{g_m G_2}{s^2 C_1 C_3 + s[G_2 C_1 + (G_1 + G_2)C_3] + (g_m + G_1)G_2} . \qquad (16)$$

Another modified circuit is obtained for setting Y_1 = sC_1, Y_2 = G_2, Y_3 = sC_3 + G_3.

The band pass filter (BP) is realized for Y_1 = G_1, Y_2 = sC_2 and Y_3 = sC_3 + G_3. For real BP, higher value of quality factor is desired. For ensuring this, the feedback is changed to be positive. It corresponds to switching of the phase of the FB current I_{FB}. Then output terminal has reversal arrow as shown in circuit diagram (Fig. 5). This biquad was symbolically analyzed by SNAP. Resulting current transfer function is

$$K(s) = \frac{a_1 s}{b_2 s^2 + b_1 s + b_0} = \frac{s C_2 g_m}{s^2 C_2 C_3 + s[G_1 C_3 + (G_1 + G_3 - g_m)C_2] + G_1 G_3} . \qquad (17)$$

Simplifications $C_1 = C_2 = C$ and $G_1 = G_2 = G$ leads to the following design equations. Center frequency and quality factor are

$$\omega_0 = \frac{G}{C}, \quad Q = \left(3 - \frac{g_m}{G}\right)^{-1} . \qquad (18)$$

Sensitivities of the center frequency are very low

$$-S_{C2}^{\omega 0} = -S_{C3}^{\omega 0} = S_{G1}^{\omega 0} = S_{G3}^{\omega 0} = 0{,}5, \quad S_{g_m}^{\omega 0} = 0, \qquad (19)$$

However the sensitivities of the quality factor are

$$-S_{C2}^{Q} = S_{C3}^{Q} = S_{G3}^{Q} = 0{,}5 - Q, \quad S_{G1}^{Q} = 0{,}5 - 2Q, \quad S_{g_m}^{Q} = 0{,}5 - 3Q, \qquad (20)$$

what indicates a little dependence of Q and some problem for design of this BP with larger *Q*.

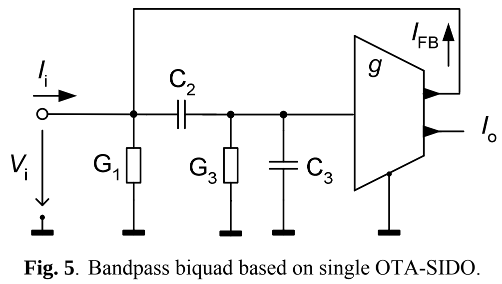

Fig. 5. Bandpass biquad based on single OTA-SIDO.

6 Structures in current mode with two feedback loops

In the chapters above we have discussed the one-loop feedback CM structures realizing several biquads. Comparable features have the structures with two-loop feedback (TLF). Fig. 6 shows two configurations of these TLF structures using signal flow graph (SFG) models.

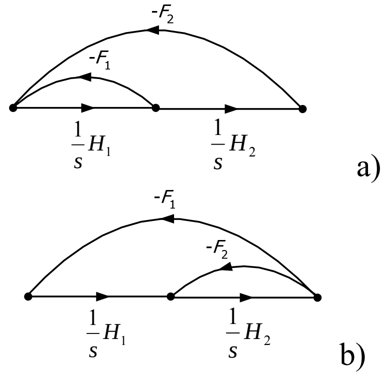

Fig. 6. Two-loop feedback CM structures.
a) Summed feedback type, b) distributed feedback type.

Both of these structures include two loops consisting two current amplifiers with gain F_k and two ideal current integrators (Fig. 3a) with transfer function (21).

$$K_j(s) = \frac{1}{s} H_j, \quad H_j = \frac{1}{\tau_j}, \tag{21}$$

The difference between these two structures is in the topology of feedback. In Fig. 6a there is the summed feedback type (SF), also called follow-the-leader feedback canonical structure. In the second one (Fig. 6b), output signal is connected to the inputs of all integrators. This structure is called distributed feedback type (DF). It is also called inverse follow-the-leader feedback. Note that in these graphs all nodes are currents.

Characteristic equation of poles can be derived from determinant of SFG. For DF structure (Fig. 6b), the determinant results in the following polynomial form

$$D(s) = s^2 + \frac{F_2}{\tau_2} s + \frac{F_1}{\tau_1 \tau_2} \quad . \tag{22}$$

Comparing (22) with the denominator of (12), the design equations are

$$\omega_o = \sqrt{\frac{F_1}{\tau_1 \tau_2}} \quad , \quad Q = \frac{1}{F_2} \sqrt{F_1 \frac{\tau_2}{\tau_1}} \, . \tag{23}$$

For given ω_C and Q, the design requires setting of the feedback coefficients F_k and the time constants τ_j.

From the equations (23) it can be easy shown that this structure has very low values of sensitivities

$$S_{F1}^{\omega o} = -S_{\tau 1}^{\omega o} = -S_{\tau 2}^{\omega o} = 0{,}5\,, \quad S_{F2}^{\omega o} = 0\,, \quad S_{F1}^{Q} = -S_{\tau 1}^{Q} = S_{\tau 2}^{Q} = 0{,}5\,, \quad S_{F2}^{\omega o} = -1 \quad . \tag{24}$$

For circuit realization of the TLF structure in the CM an appropriate action is taken to modify and complete the basic SFG (Fig. 6). In Fig. 7 is shown the complete SFG of the DF-TLF structure developed from basic SFG on Fig. 6b by completing with all possible input (I_i) and output (I_o) currents. Note that the untagged branches have the gain value equal one.

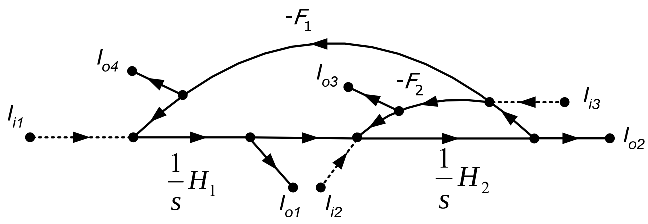

Fig. 7. SFG model of the TLF-DF-CM structure.

The SFG given in Fig. 7 can be realized by two OTA-SIMO ideal current integrators (Fig. 3a) and two OTA-SIMO current amplifiers (Fig. 2c). The resulting circuit diagram is shown in Fig. 8. Symbolical analyzing in SNAP, following design equations are obtained

$$\omega_p = \sqrt{\frac{g_{m1}g_{m2}g_{m4}}{C_1C_2G_3}}, \quad Q = \frac{1}{g_{m3}}\sqrt{\frac{g_{m1}g_{m4}G_3C_1}{g_{m2}C_2}}. \tag{25}$$

This analysis also shows that the proposed circuit is able to realize multifunctional frequency filter with transfer functions of types (LP, BP, HP). Fig. 8 describes connection of inputs and outputs to the structure of the filter. For example if the input current is I_{i1} and the output current is I_{o2}, LP transfer function is obtained

$$K_{12}(s) = \frac{I_{o2}}{I_{i1}} = \frac{g_{m1}g_{m2}G_3}{s^2C_1C_3G_3 + sC_1g_{m2}g_{m3} + g_{m1}g_{m2}g_{m4}}. \tag{26}$$

for input current I_{i2} and output current I_{o3}, BP is obtained

$$K_{23}(s) = \frac{I_{o3}}{I_{i2}} = \frac{-sg_{m1}g_{m3}C_2}{s^2C_1C_3G_3 + sC_1g_{m2}g_{m3} + g_{m1}g_{m2}g_{m4}}. \tag{27}$$

Presented structure in Fig. 8 can be simplified if feedback coefficients F_k are set to one ($F_1 = F_2 = 1$) or are set to the same value $F_1 = F_2$. On the other hand the current distributor (Fig. 2a) can be connected to the input of this circuit implementing a common multiple driving (I_{i1}, I_{i2}, I_{i3}, dot lines in Fig. 8) to produce universal biquadratic characteristic. More complex transfer function is also obtained if the output currents I_{o1}, I_{o2}, I_{o3} and I_{o4} in Fig. 8.are summed.

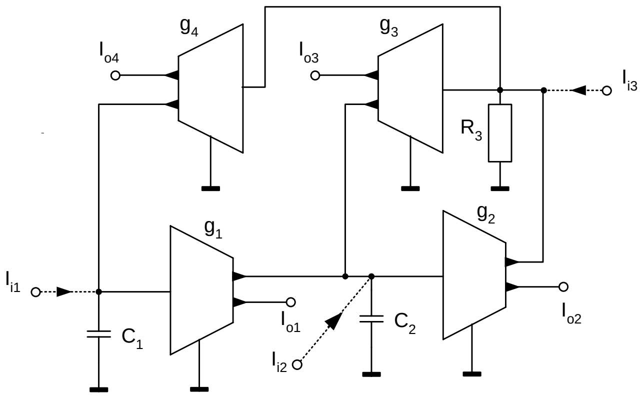

Fig. 8. Two-loop distributed feedback biquad in current mode.

Similar CM structures, which are composed of two lossless integrators in loop with summator have been already discussed in [9] and [16].

7 Adjoint VM-CM transformation

The CM circuit can be obtained from the VM prototype using the adjoint VM-CM transformation. The principle of this method was described in [2]. The adjoint transformation can be also applied in the circuit based on the OTA. Note that after application of the transformation, the nodes of input voltages are transformed to nodes of output currents and reversely nodes of output voltages are transformed to nodes of input currents. Also active functional blocks of the prototype are replaced by adjoint counterparts. In the case of the OTA-DISO the corresponding adjoint active block is OTA-SIDO where input and output ports are mutually interchanged. The resulting adjoint network has equivalent transfer function like transfer function of its prototype. Note that the OTA-SIDO can be generalized to OTA-SIMO. The other ports can be used as the outputs of the hole filter (see OTA-2 in Fig. 9b).

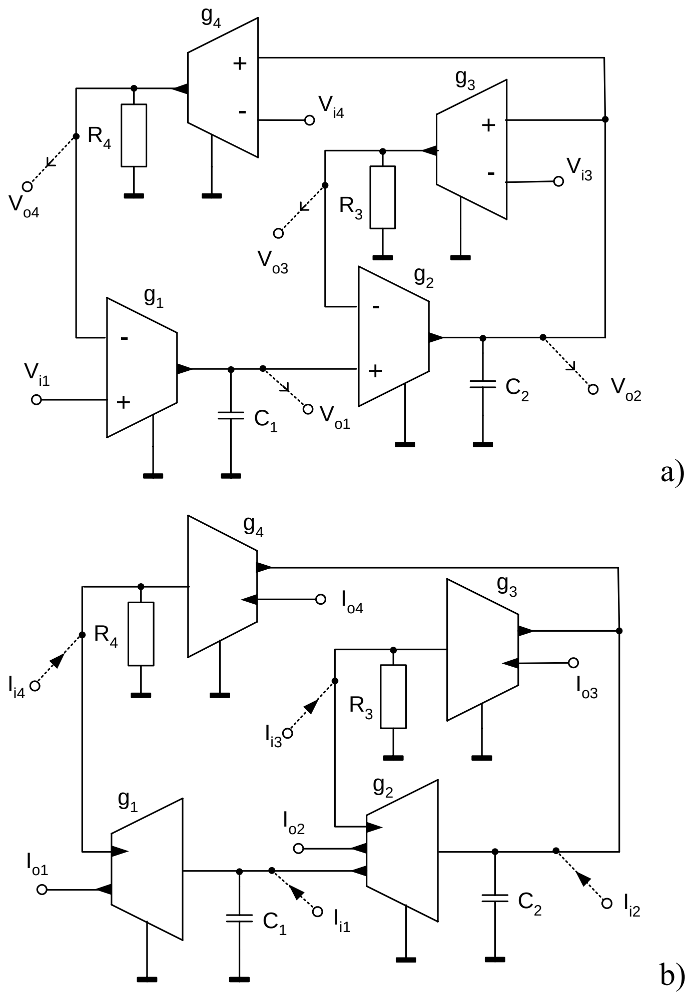

Fig. 9. Adjoint VM-CM transformation.
a) Distributed feedback voltage mode 2-nd order structure,
b) Adjoint summed feedback current mode structure.

As an illustrating example, the OTA-DISO voltage mode TLF-DF structure from [9] (Fig. 9a) was chosen as a prototype. Applying the adjoint transformation, the DF-VM structure (Fig. 6b) is transformed to the structure SF-CM (Fig. 6a). The resulting circuit is shown in Fig. 9b. This multifunctional biquad (Fig. 9b) was detailed described in [7]. LP, BP, HP transfer functions can be easy realized using different inputs and outputs. All passive elements (R and C) are grounded, which is suitable for practical fabrication.
Band reject filter or modified LP and HP filters with zeros can be obtained if certain output signals are summed.

8 Current mode multiple loop structures

Advantage of the OTA-SIMO is superb in the current mode multi-loop feedback (MLF) structures [12], especially if more current distributions are used. The general current transfer function of any order (n)

$$K(s) = \frac{I_{out}}{I_{inp}} = \frac{a_n s^n + a_{n-1} s^{n-1} + ... + a_1 s + a_0}{b_n s^n + b_{n-1} s^{n-1} + ... + b_1 s + b_0} \tag{28}$$

can be directly implemented by one of the MLF structures well known in the classical VM. For the CM, second canonical analog structure *follow-the-leader feedback* (FLF) *with output summation* (FLF-OS) is the most suitable. Big advantage of current mode is very easy realization of summations of currents by only single node connection. The basic SFG model of FLF-OS-CM corresponding to formula (28) was presented in [12]. However the circuit realization of this SFG needs a lot of multipliers (multiplication by coefficients a_i, b_i) what is reason for rearranging the transfer function (28) to the following form

$$K(s) = \frac{\frac{a_n}{b_n} + \frac{a_{n-1}}{sb_n} + \frac{a_{n-2}}{s^2 b_n} + ... + \frac{a_1}{s^{n-1} b_n} + \frac{a_0}{s^n b_n}}{1 + \frac{b_{n-1}}{sb_n} + \frac{b_{n-2}}{s^2 b_n} + ... + \frac{b_1}{s^{n-1} b_n} + \frac{b_0}{s^n b_n}}. \tag{29}$$

The modified SFG corresponding to (29) is shown in Fig. 10. The gain of some of the branches is set to one and half of the multipliers can be omitted and replaced by direct connections.

To illustrate the structure FLF-OS-CM based on OTA-SIMO, universal 4th-order multifunctional (LP, BP, HP) filter was chosen. For this case the SFG from Fig. 10 can be rearranged to the form given in Fig. 11.

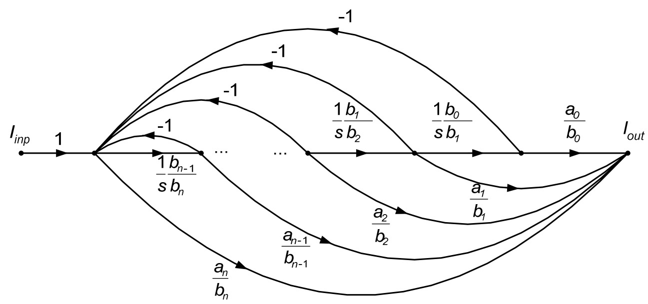

Fig. 10. Modified SFG of the structure FLF-OS-CM.

The circuit realization of this SFG (Fig. 11) requires four current integrators (Fig. 3a) implemented in branches in direct path (1/s) and one current distributor implemented in the first node. The current distributor can be omitted if HP output is not required. In this case the simplest variant shown in Fig. 12 is obtained. This structure is suitable for integrated form because all capacitors are grounded. Four OTAs with two or three current outputs are implemented. To obtain other BP with asymmetrical characteristic, OTA 1 (g_{m1}) and OTA 3 (g_{m3}) are supplemented by current outputs (BP_A). The BP is standard symmetrical BP of the 4th-order. The transfer function of BP is

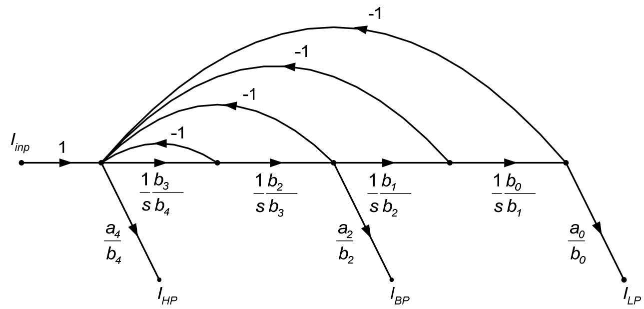

Fig. 11. The SFG of the multifunctional 4th-order filter.

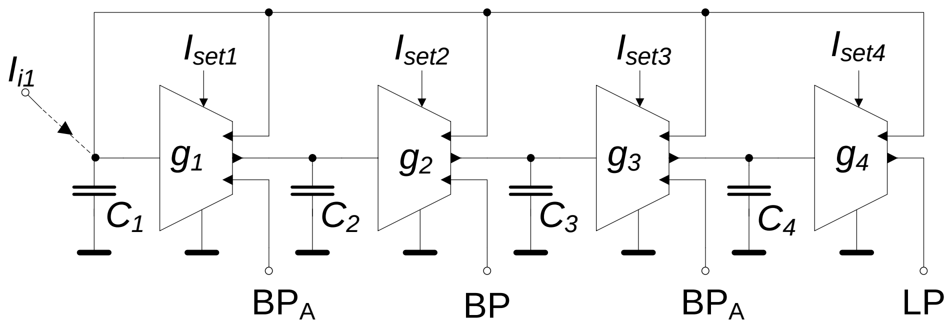

Fig. 12. Electronically tuned multifunctional 4th-order filter.

$$K_{BP}(s)=\frac{I_{BP}}{I_{i1}}=\frac{-a_o}{b_4s^4+b_3s^3+b_2s^2+b_1s+b_0}\quad. \tag{30}$$

The LP transfer function is

$$K_{LP}(s)=\frac{I_{LP}}{I_{i1}}=\frac{-a_2s^2}{b_4s^4+b_3s^3+b_2s^2+b_1s+b_0}. \tag{31}$$

In general formulas (30) and (31), the relationship between coefficients and circuit components are

$$b_4=1,\quad b_3=\frac{g_{m1}}{C_1},\quad b_2=a_2=\frac{g_{m1}g_{m2}}{C_1C_2},\quad b_1=\frac{g_{m1}g_{m2}g_{m3}}{C_1C_2C_3},\quad b_0=a_0=\frac{g_{m1}g_{m2}g_{m3}g_{m4}}{C_1C_2C_3C_4}. \tag{32}$$

If transconductances are set to

$$g_{m2}=g_{m1}/2,\ g_{m3}=g_{m1}/3.41,\ g_{m4}=g_{m1}/6.83 \tag{33}$$

the filter can be simply electronically tuned by control current $I_{SET.}$ Relationship between control current I_{SET} and trasconductance g_m is linear. Similar second-order filter has been presented in [11].

9 Simulation results

In the simulation of OTA-SIMO on transistor level of description (Fig. 1), models of BJT are used. In [17], these models are used for realization of multi-output current followers. These models of OTA have few advantages. The first one is linear dependence of g_m on DC control current I_{SET} ($g_m \sim 20.I_{SET}$ in the range between 10 uA and 1 mA and for $V_{CC} = \pm 2.5$ V). The second one is lower input voltage offset in comparison to noncascode CMOS realization. Finally, frequency bandwidth is approximately 250 MHz. Disadvantages are lower input impedance, frequency dependence of input impedance and higher power consumption.

The second order BP filter is given in Fig. 5. It was designed for: center frequency f_C = 1 MHz, maximally flat (Butterworth filter) pass-band, gain K_C = -3 dB, stop-band frequency f_s =3 MHz, for the minimum damping K_s = - 15 dB. Resulting coefficients of the denominator of (17) are

$$b_0 = 3{,}93449.10^{13}, \quad b_1 = 8{,}87072.10^{6}, \quad b_2 = 1. \tag{34}$$

Choosing $C_2 = C_3 = 470$ pF, values of other components are

$$G_1 = G_3 = \sqrt{b_0}.C = 2{,}9\ mS \quad \text{and} \quad g = 3G - b_1 C = 4{,}5\ mS\ . \tag{35}$$

The circuit from Fig. 5 using these components values (35) and model of OTA on transistor level of description (Fig. 1b), was simulated by PSpice. The resulting magnitude response is shown in Fig. 13.

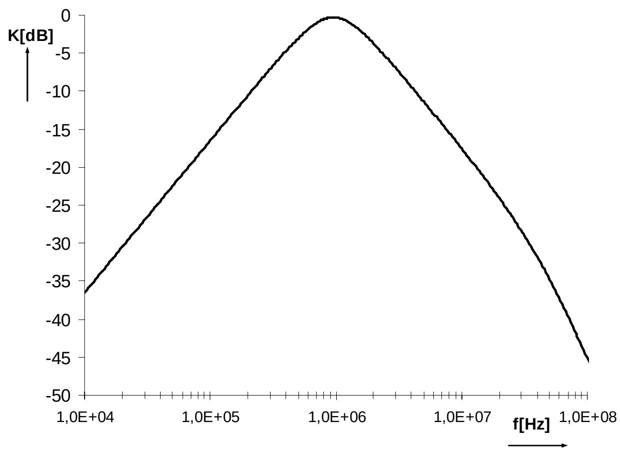

Fig. 13. Simulated magnitude response of the BP biquad (Fig. 5).

Similarly the two-loop distributed feedback multifunctional biquad from Fig. 8 was verified for f_0 = 1 MHz and quality factor Q = 1. Choosing $C_2 = C_3$ = 1 nF, $G_3 = G_4$ = 10 mS, $g_{m3} = g_{m4}$ = 10 mS ($I_{SET3} = I_{SET4}$ = 500 uA) and in accordance to (25),transconductances are set $g_{m1} = g_{m2} = g_m$ = 6.3 mS ($I_{SET1} = I_{SET2}$ = 315 uA).

Simulated magnitude responses of the filter are given in Fig. 14. Transfer functions of types LP (I_{O1}/I_{I3}), BP (I_{O2}/I_{I3}), BR (I_{O3}/I_{I3}) and HP (I_{O3}-I_{O1}/I_{I3}) are obtained. Varying of transconductance g_3, values of quality factor Q and basic gain K_0 are adjusted. As one can see from (25), (26) and (27), it is not possible to adjust Q, K_0 and f_C independently.

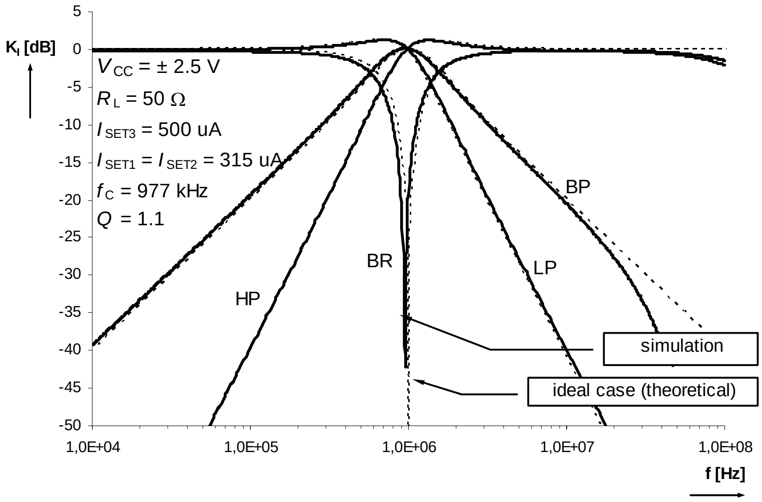

Fig. 14. Simulated magnitude responses of the BP biquad from Fig. 8.

The fourth order multifunctional filter of the FLF-OS-CM structure based on OTA-SIMO (Fig. 12) was designed for the following specification: maximally flat Butterworth filter, LP and symmetrical BP type, cut-off frequency and center frequency $f_C = f_0 = 1$ MHz, minimum pass-band gain $K_C = -3$ dB, stop-band frequency $f_s = 3$ MHz, for the minimum damping $K_s = -35$ dB. The corresponding coefficients of the denominator of (28) are $b_0 = 1{,}56207.10^{27}$, $b_1 = 6{,}49284.10^{20}$, $b_2 = 1{,}34940.10^{14}$, $b_3 = 1{,}64280.10^{7}$, $b_4 = 1$. Using design equations (32) and setting all capacitors $C_1 = C_2 = C_3 = C_4 = C = 470$ pF, following values of transconductances are obtained $g_{m1} = 7{,}72$ mS, $g_{m2} = 3{,}86$ mS, $g_{m3} = 2{,}26$ mS, $g_{m4} = 1{,}13$ mS. The resulting Pspice magnitude responses are given in Fig. 15. If all transconductances (g_m) are varied simultaneously, the filter can be very easy tuned. The tuning of the LP filter is shown in Fig 16. Also BP is tuned. Description of simulated results of Fig. 15 and Fig. 16 is summarized in Tab. 1.

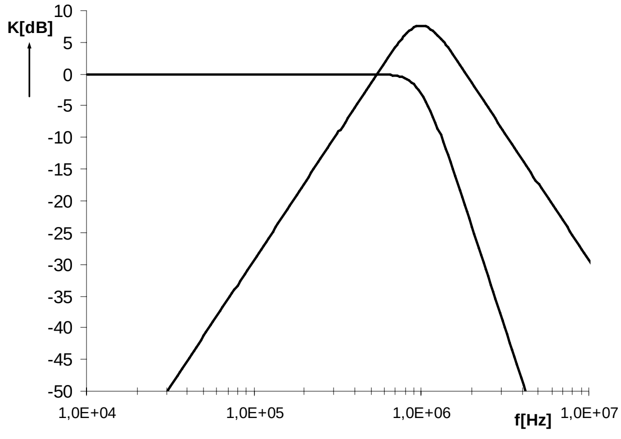

Fig. 15. Simulated magnitude responses of the 4th order filter (Fig. 12).

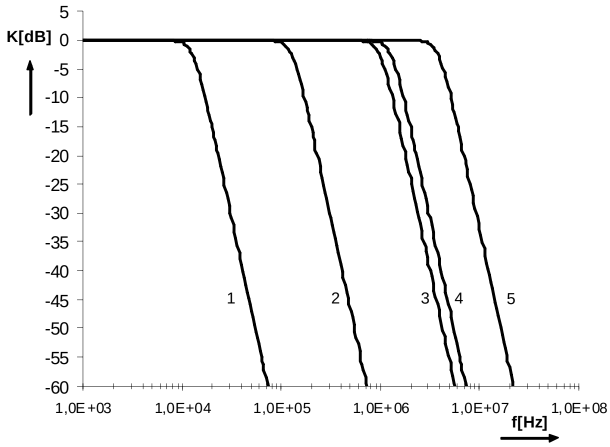

Fig. 16. Simulation of the tuning of the LP filter (Fig. 12).

Tab. 1.Controlling the cut-off frequency by the transconductance g_1.

Curve index	g_1 [mS]	$f_{-3\,dB}$ [kHz]
1	0,1	13
2	1,0	130
3	7,72	1 000
4	10,0	1 260
5	30,0	3 890

10 Conclusion

Transconductors (OTAs) with multiple outputs are suitable for using especially in current mode circuit. Multi-output active blocks give more flexibility in design of frequency filters. The paper described how to use OTA-SIMO block for realization of multi-outputs current distributor, multi-outputs current integrator and multi-outputs current amplifiers. One-loop, two-loop and multi-loop filter structures in current mode were discussed. Design procedure is based on the signal flow graph technique. In the current mode multi-loop feedback structures the OTA-SIMOs are basic building blocks. In most of second-order applications, two or three-output active blocks are sufficient. The adjoint VM-CM transformation was used for transformation of VM prototype to new OTA-SIMO based circuits. Designed circuits were verified in Pspice using models of OTAs on transistor level. Simulation confirmed that designed circuits are suitable for high frequency applications in video band.

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