Current-Controlled Current-Mode Universal Biquad Employing Multi-Output Transconductors

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Abstract. *This paper deals with RC active biquad working in the so-called current mode (CM). The design approach uses only three transconductors (OTA) with the minimum necessary number of outputs and with only three passive grounded elements. The proposed filter has simple circuit configuration providing all standard transfer functions such as high-pass (HP), band-pass (BP), low-pass (LP), band-reject (BR) and all-pass (AP). Electronic tuning and independent adjusting of the quality factor and bandwidth of BP filter is possible. The presented circuits are verified by PSpice simulations utilizing OTAs on transistor level of abstraction. The linear parasitic effects of the real active elements in each suggested circuit are briefly discussed. Experimental verification is also given. Designed networks can be used in many applications such as antialiasing filters, in high-speed data telecommunication systems, for signal processing in the cable modems, in regulation and measurement techniques etc.*

Keywords

Current-mode, transconductor, electronic adjusting, universal filter.

1. Introduction

Recent trends focused on adjustable applications require modern electronically controllable active building blocks, i.e. blocks where main transfer parameter can be controlled by external dc voltage or current. For example in the case of voltage amplifiers this parameter is voltage gain, current amplifiers are characterized by current gain, for transconductance amplifiers it is transconductance, etc. There is also possibility of using single OTA as electronically controlled resistors as it is demonstrated in [1], [2]. Digital potentiometers and D/A converters are suitable for electronically adjustable applications. The advantage of digital potentiometers is easy controlling of their value through a personal computer. However, several serious drawbacks such as low maximal amplitude of signal, high parasitic capacitance (tens of pF) resulting into decreased maximal frequency of processed signal (few MHz) make them less useful. Also low number of steps in some types of the digital potentiometers can cause problems. There are many active blocks well suited for electronic control purposes in the interesting publication [3]. Unfortunately the majority of them is hypothetical and can not be bought in shop.

For many low frequency applications, classical active RC filters [4] based on voltage operational amplifiers are often used. However at higher frequencies and for tunable applications, it is better to replace the conventional opamps by some OTAs [5], [6], [7], current differencing transconductance amplifiers (CDTAs) [8], dual or multi-output current-controlled current conveyors (DO-CCCIIs) [9], [10], [11], or current-controlled current feedback amplifiers (CC-CFAs) [12]. Uncommon devices mentioned above have advantageous features like higher speed of signal processing and implementation in full integration form using modern bipolar, CMOS, BiCMOS and GaAs technologies. The transconductance (g_m) of OTAs and CDTAs can be electronically tuned by means of current I_{SET} allowing the desired external control of circuit parameters without need to change values of passive elements. The circuits based on OTAs and working in the voltage mode (VM) are already covered by the flock of journal and book articles [4]-[7] since it is a topic of interest for many years. These structures contain mostly voltage amplifiers, voltage integrators and voltage feedback. Differential-input single-output OTAs (OTA-DISO) are usually used in these integrators and amplifiers [13], [14]. It is still believed that CM signal processing [5] applications have wider bandwidth, higher speed, lower dc voltage, lower power biasing and bigger simplicity of a final circuit. Instead of the DISO type of OTA, the OTA with single-input and multiple-outputs is used. The multiple-output transconductors are not off-the-shelf components which are commonly employed in practice. On the other hand it is profitable to have an active block with more than one output, especially in the case of CM circuits. This can be solved by a parallel connection of OTA-DISO inputs but at the cost of increasing complexity of the circuit, too expensive circuit realization and also higher power consumption. Also possibility of miniaturization is lost. Nevertheless it is not technologically difficult to implement several current outputs inside the internal structure of OTA block. The major part of the previously published solutions utilizes different technologies like CMOS or BiCMOS which are not accessible in general. In this paper OTA with high-speed commercially available bipolar transistor array is used for PSpice verifications.

The existing publications involving similar problems from the area of direct state-variable synthesis of the active filters [15] with OTA are still indispensable aimed on OTA-DISO. Moreover many authors design their circuits on the low frequency band about several kHz where VM approaches are valid and CM is not reasonable. This proposition holds not only for filters (for example [16]) but also for the rest of applications. The universal filter presented in [17] can work in VM as well as CM but contains up to seven active OTA-DISO blocks. Evident possibility of electronic adjusting is not verified. It is obvious that only simple modifications are necessary to change our proposed filter from CM to VM. In detail, input voltage to current converter and adequate output resistive loads are needed. The circuitry representing multiple-input and single-output universal filter with five OTAs is provided in [18]. To reach BR and AP transfer functions another active block known as current distributor is necessary. Its function is to copy input current to several corresponding nodes. The proposed solution is better also from this viewpoint since BR and AP filter can be obtained by interconnection of OTA outputs without any other component. Filter with four OTA is given in [19] where some multiple-output OTAs are already presented. In spite of this, electronic adjusting of the filter parameters is still missing. If compared to our network slightly similar structure with five-output OTA is provided. In our work it is proved that three outputs are sufficient for universal filter design. Using a pair of OTAs and single VM differential difference current conveyor (DDCC) as universal filter is given in [20]. This is indeed an interesting network but its proper function is a question since there are no simulations or measurements. CM filter consisting of four dual-input dual-output OTA (OTA-DIDO) is given in [21]. Unfortunately, to obtain some transfer functions it is necessary to feed input current to several network nodes simultaneously. The structure similar to the one presented (four-output OTAs) in this paper is shown in [22]. It is quite difficult to compare both filters since there are no results in this publication. Multiple-input filter with three OTA integrators with five outputs is presented in [23]. In our case there are separate outputs for all responses if compared to [8]. The possibility to electronically tune BP filter's bandwidth also beats [8]. Multiple-input single-output filter with CDTA modeled on bipolar transistor level can be found in [24]. KHN filter employing only two OTAs with three and five outputs is given in [25]. Its drawback is the missing electronic control of quality factor and bandwidth in the case of BP filter. The modification removing this obstacle is in [26]. But this structure needs up to five active blocks.

2. Transconductor OTA-SIMO

This active block is very suitable for applications in CM filters. Commercially available OTAs can work on high frequencies, for example OPA 860 [27], LT 1228 [28], etc. However, the disadvantage of these parts is in the lack of outputs, these devices mostly have only one current output what is insufficient for many CM circuits. Schematic symbol of the OTA-SIMO is shown in Fig. 1.

Such device has two positive and two negative outputs. Note that only three outputs are necessary in the further text. In the ideal case, OTA is voltage-controlled current source and it is described by the following equations

$$I_{o1} = I_{o2} = -I_{o3} = -I_{o4} = g_m \cdot V_{INP}. \quad (1)$$

The transconductance denoted as g_m can be controlled by external dc current I_{SET} providing the possibility of electronic control of the OTA based circuit's parameters. Typical values of g_m are in the range of tens to hundreds of µS for CMOS technology and up to few mS for BJT technology.

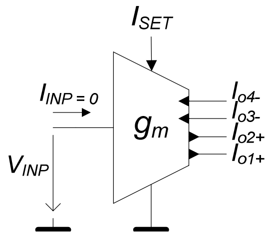

Fig. 1. Symbol of four-output transconductor.

Input and output resistances of real OTA are very high (from hundreds of kΩ to tens of MΩ). Parasitic input and output capacitances are very small (few pF). These components can operate in the frequency range of several hundreds of MHz. The structure in Fig. 2 was adopted from [2] while making only small changes - inverting input was grounded and another current mirror stages were added. A similar circuit in the CMOS technology with five outputs was given in [25].

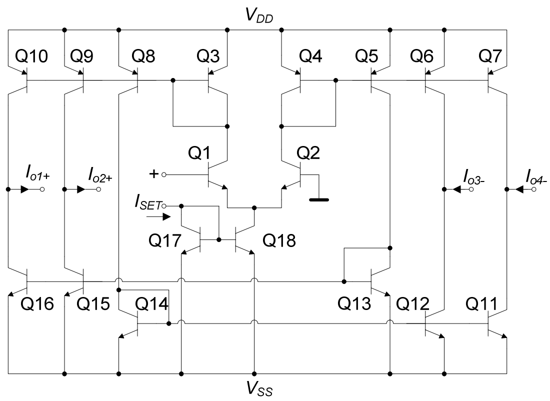

Fig. 2. Inner structure of four-output transconductor.

The active block in Fig. 2 was simulated by using professional models of transistor array [29] with parameters summarized in Fig. 3. The main advantage of this OTA is in very linear dependence of g_m on dc control current I_{SET}. The transconductance is $g_m \sim 20.\ I_{SET}$ in range between 10 μA to 1 mA and for $V_{CC} = \pm 2.5$ V. GBW is about 250 MHz. Input-output characteristics of this device are given in Fig. 4 and open-loop frequency curves are visible by means of Fig. 5 for few values of I_{SET} and g_m respectively. To this end, g_m as a function of I_{SET} is provided by Fig. 6.

Thanks to the used array's bipolar technology OTA's input resistance R_{inp} [25] is lower than in the case of CMOS realization and is dependent on I_{SET} (I_{bias}) and frequency. To be more specific it is about 1.5 MΩ down to several tens of kΩ, i.e. decreases with increasing I_{SET}, similar as it is for commercially available OTA [2]. Output resistance R_{out} varies from hundreds of kΩ up to several units of MΩ. The problems associated with the parasitic properties will be analyzed in detail in specific chapter.

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.model PUHFARRY PNP
+ (IS= 1.020E-16  XTI= 3.000E+00  EG = 1.110E+00  VAF= 3.000E+01
+ VAR= 4.500E+00  BF = 7.011E+01  ISE= 1.020E-19  NE = 1.400E+00
+ IKF= 7.500E-02  XTB= 0.000E+00  BR = 7.000E+00  ISC= 1.020E-14
+ NC = 1.800E+00  IKR= 7.500E-02  RC = 3.800E+01  CJC= 4.270E-13
+ MJC= 3.000E-01  VJC= 1.230E+00  FC = 5.000E-01  CJE= 4.800E-13
+ MJE= 5.700E-01  VJE= 8.800E-01  TR = 4.000E-09  TF = 33.91E-12
+ ITF= 7.127E-01  XTF= 4.514E+01  VTF= 1.000E+01  PTF= 0.000E+00
+ XCJC=1.756E-01  CJS= 1.689E-13  VJS= 7.500E-01  MJS= 0.000E+00
+ RE = 1.333E+00  RB = 3.740E+01  RBM= 0.000E+00  KF = 0.000E+00
+ AF = 1.000E+00)
.model NUHFARRY NPN
+ (IS= 1.875E-16  XTI= 3.000E+00  EG= 1.110E+00  VAF= 6.000E+01
+ VAR= 4.500E+00  BF = 1.461E+02  ISE=1.875E-19  NE = 1.400E+00
+ IKF= 7.500E-02  XTB= 0.000E+00  BR= 1.000E+01  ISC= 1.875E-14
+ NC = 1.800E+00  IKR= 7.500E-02  RC= 2.940E+01  CJC= 2.818E-13
+ MJC= 2.400E-01  VJC= 9.700E-01  FC= 5.000E-01  CJE= 3.900E-13
+ MJE= 5.100E-01  VJE= 8.720E-01  TR= 4.000E-09  TF= 17.850E-12
+ ITF= 1.155E+00  XTF= 7.881E+01  VTF=1.000E+01  PTF= 0.000E+00
+ XCJC=1.756E-01  CJS= 1.689E-13  VJS=7.500E-01  MJS= 0.000E+00
+ RE = 1.333E+00  RB = 3.518E+01  RBM=0.000E+00  KF = 0.000E+00
+ AF = 1.000E+00)
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Fig. 3. Individual parameters of the transistors.

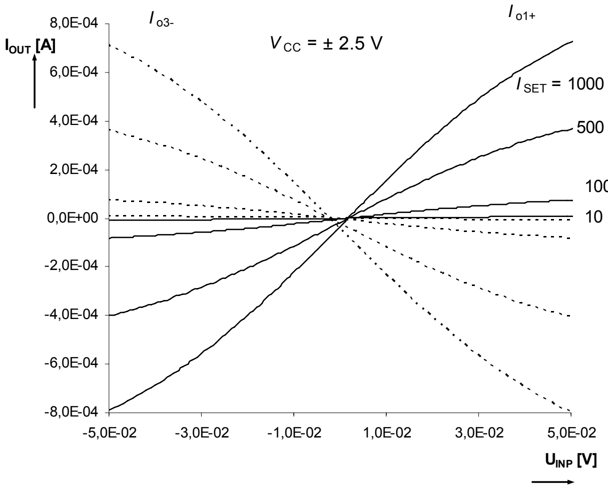

Fig. 4. Input-output characteristics of the OTA.

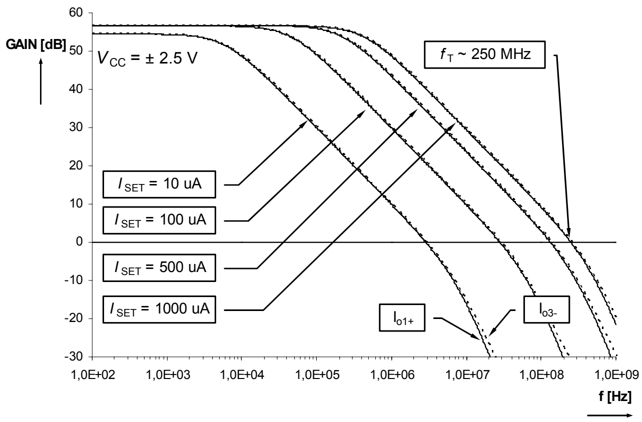

Fig. 5. Open loop gain frequency responses of the OTA.

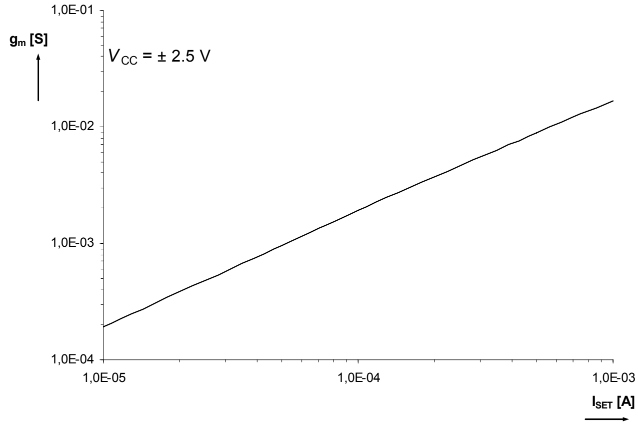

Fig. 6. Transconductance versus I_{SET}.

3. Proposed Universal Filter

The multifunctional biquad under inspection is given in Fig. 7. Note that it is composed of three multiple-output OTAs and three grounded passive elements. Symbolical analysis reveals that it is possible to obtain all transfer functions including second-order band reject (BR) filter. Modification for obtaining of all pass filter response (AP) is shown in Fig. 8. The transfer functions of the filter provided in Fig. 7 and Fig. 8 are

$$K_{LP}(s) = \frac{N(s)}{D(s)} = \frac{I_{OUT\_LP}}{I_{INP}} = \frac{\dfrac{g_{m1} g_{m2} g_{m3} R}{C_1 C_2}}{s^2 + \dfrac{g_{m1} g_{m3} R}{C_1} s + \dfrac{g_{m1} g_{m2}}{C_1 C_2}}, \quad (2)$$

$$K_{BP}(s) = \frac{I_{OUT\_BP}}{I_{INP}} = \frac{\dfrac{g_{m1} g_{m3} R}{C_1} s}{s^2 + \dfrac{g_{m1} g_{m3} R}{C_1} s + \dfrac{g_{m1} g_{m2}}{C_1 C_2}}, \quad (3)$$

$$K_{BR}(s) = \frac{I_{OUT\_BR}}{I_{INP}} = -\frac{g_{m3} R s^2 + \dfrac{g_{m1} g_{m2} g_{m3} R}{C_1 C_2}}{s^2 + \dfrac{g_{m1} g_{m3} R}{C_1} s + \dfrac{g_{m1} g_{m2}}{C_1 C_2}}, \quad (4)$$

$$K_{HP}(s)=\frac{I_{OUT\_HP}}{I_{INP}}=\frac{g_{m3}Rs^2}{s^2+\dfrac{g_{m1}g_{m3}R}{C_1}s+\dfrac{g_{m1}g_{m2}}{C_1C_2}}. \tag{5}$$

For the AP filter in Fig. 5 the transfer function is

$$K_{AP}(s)=\frac{g_{m3}Rs^2-\dfrac{g_{m1}g_{m3}R}{C_1}s+\dfrac{g_{m1}g_{m2}g_{m3}R}{C_1C_2}}{s^2+\dfrac{g_{m1}g_{m3}R}{C_1}s+\dfrac{g_{m1}g_{m2}}{C_1C_2}}. \tag{6}$$

The characteristic frequency and quality factor is

$$\omega_C=\sqrt{\frac{g_{m1}g_{m2}}{C_1C_2}},\quad Q=\frac{C_1}{g_{m1}g_{m3}R}\sqrt{\frac{g_{m1}g_{m2}}{C_1C_2}}. \tag{7), (8}$$

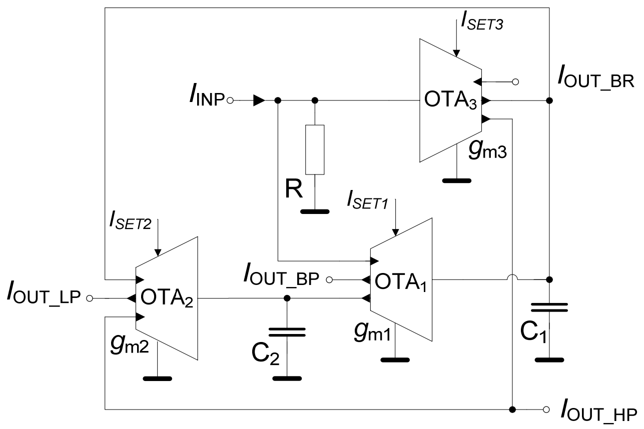

Fig. 7. Current mode biquad.

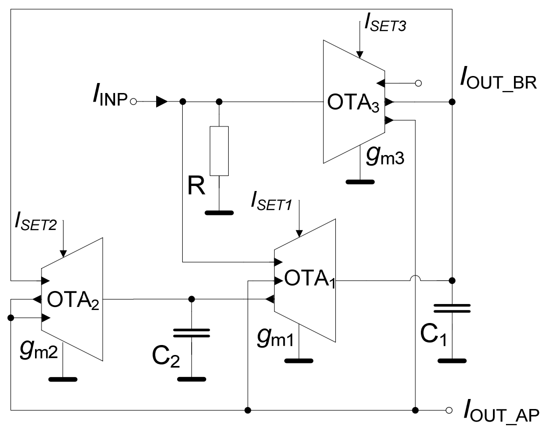

Fig. 8. Modification for AP filter.

The relative sensitivities of the characteristic frequency and quality factor with respect to the circuit parameters are

$$S_{g_{m1}}^{\omega_C}=S_{g_{m2}}^{\omega_C}=-S_{C_1}^{\omega_C}=-S_{C_2}^{\omega_C}=0.5,\quad S_{g_{m3}}^{\omega_C}=S_{R}^{\omega_C}=0, \tag{9), (10}$$

$$S_{g_{m2}}^{Q}=-S_{g_{m1}}^{Q}=-S_{C_2}^{Q}=S_{C_1}^{Q}=0.5,\quad S_{g_{m3}}^{Q}=S_{R}^{Q}=-1. \tag{11), (12}$$

As follows from equations (7) and (8) if $g_{m1}=g_{m2}$ holds characteristic frequency ω_C and quality factor Q can be tuned independently on each other.

In practice, synchronous change of both transconductances is not always an easy task because it is affected by matching errors of the current outputs of OTAs as well as by control mechanism. By adjusting R or better g_{m3} quality factor and bandwidth (3), (8) of BP response can be changed.

4. Simulation Results

The proposed filter is designed for the characteristic frequency f_C = 1 MHz, quality factor Q = 1. To reduce computations there are some additional assumptions like $g_{m3}R = 1$, $g_{m1} = g_{m2} = g_m$. Passive elements were chosen as $R = 100\ \Omega$ and $C_1 = C_2 = C = 1$ nF. Then $g_{m3} = 10$ mS leads to $I_{SET3} = 500\ \mu$A and the value of g_m calculated using (7) is 6.3 mS resulting into $I_{SET1} = I_{SET2} = 315\ \mu$A. Finally, the magnitude responses are shown in Fig. 9. The value of f_C obtained by simulation is about 977 kHz with associated Q = 1.1. An example of adjusting BR filter is given by simulation in Fig. 10. Characteristic frequency range is between 455 kHz and 3 MHz (see Tab. 1).

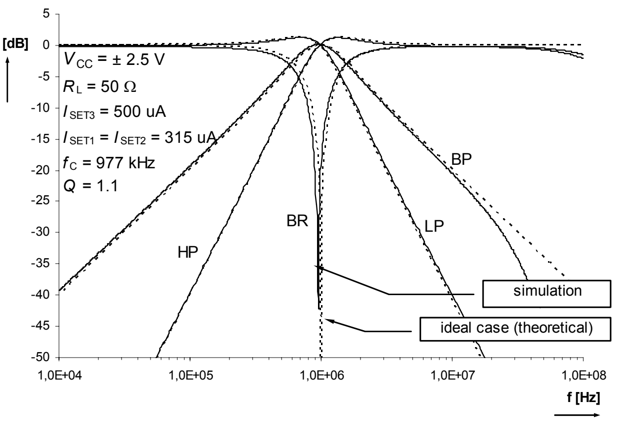

Fig. 9. Magnitude responses of the filter in Fig. 4.

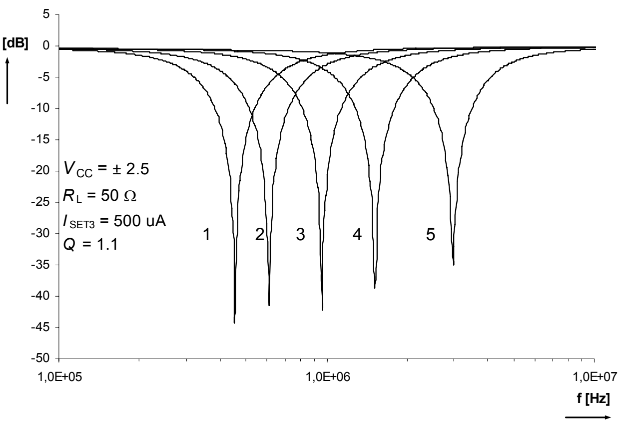

Fig. 10. Tuning of the BR response.

Transfer constant K_0 is varying simultaneously with quality factor Q what makes adjusting of BP bandwidth possible as it is documented in Fig. 11. The important values are summarized in Tab. 2.

The frequency characteristics of the AP filter are shown in Fig. 12 and group delay is depicted by means of Fig. 13. It seems that changes of g_{m3} affect except other transfer function's quality factors also their basic constant K_0 as it is visible in Fig. 14. Although this event evidently concerns also the filter presented in [22] it is not mentioned here. In the case of other widely used LP and HP filters the bandwidth is changed together with f_C which is very easy if condition $g_{m1} = g_{m2}$ is fulfilled. Transient response of the BP filter is visible in Fig. 15 and stability testing with rectangular input signal is shown in Fig. 16.

index	I_{SET1}, I_{SET2} [uA]	f_C [kHz]
1	150	455
2	200	616
3	315	977
4	500	1 540
5	1 000	3 040

Tab. 1. Values of f_C from Fig. 10.

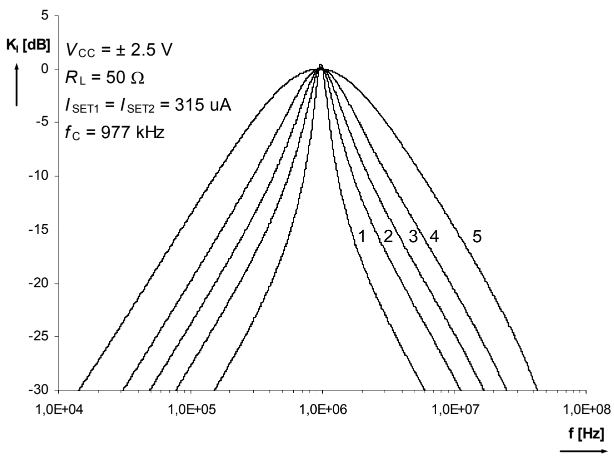

Fig. 11. Adjusting Q and bandwidth of BP response.

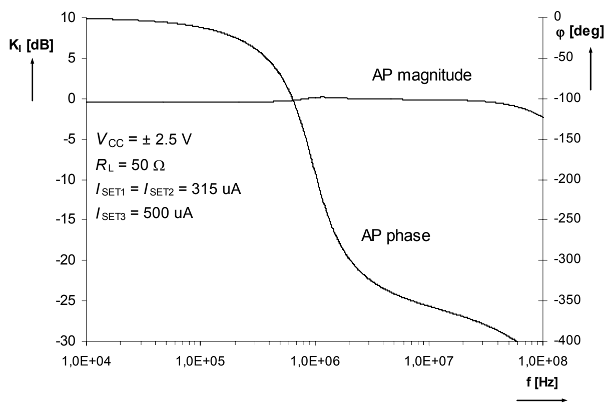

Fig. 12. Frequency characteristics of the AP filter.

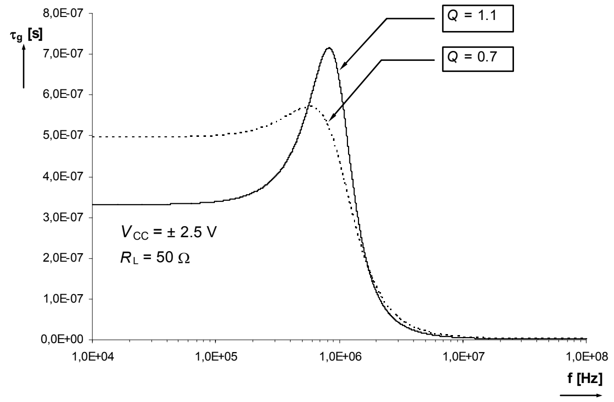

Fig. 13. Group delay of the AP filter.

index	I_{SET3} [uA]	Q [-]	BW (-3 dB) [kHz]
1	100	5.3	184
2	200	2.7	376
3	315	1.7	596
4	500	1.1	945
5	1 000	0.7	1 870

Tab. 2. Values for Fig. 11.

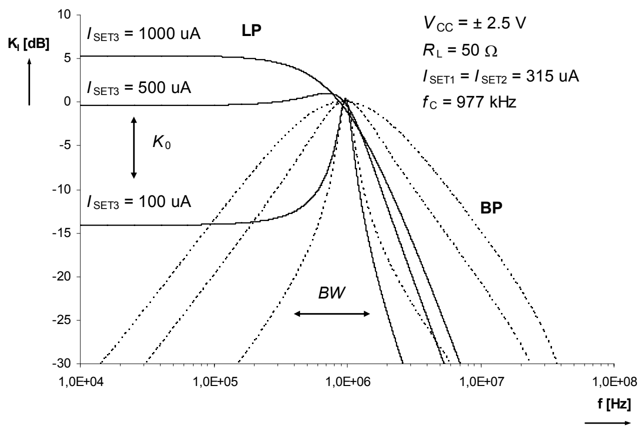

Fig. 14. Influence of g_{m3} on K_0, Q and filter bandwidth.

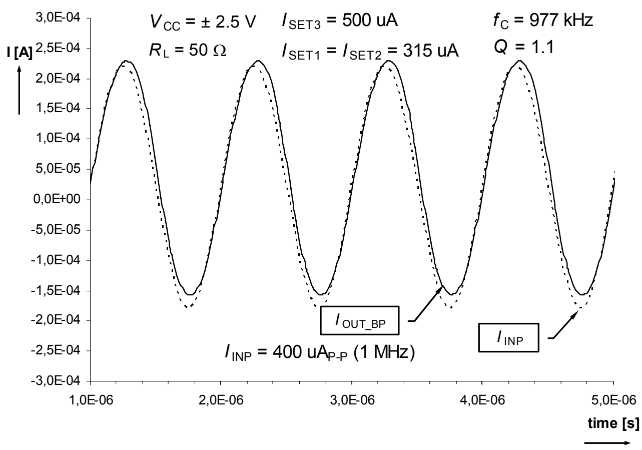

Fig. 15. Transient response of the BP filter.

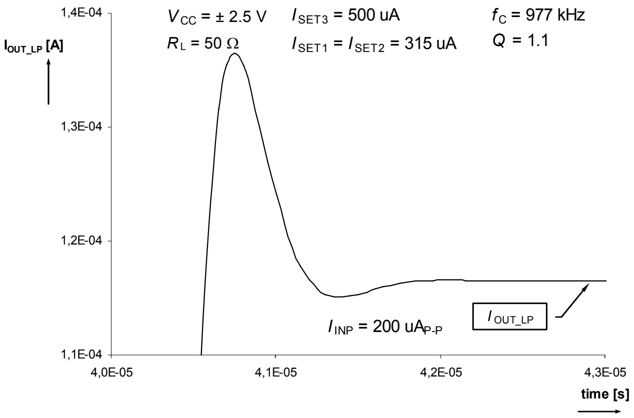

Fig. 16. Detail of the LP filter jump-function response.

5. Influences of Parasitic Elements

The network model given in Fig. 17 is adopted for studying parasitic properties. Intuitively, the parasitic input or output resistances of OTA device are represented by conductances G_{out} and G_{inp} where a number specifies a concrete OTA. The parasitic capacitances are denoted analogously as C_{inp} and C_{out}. For individual combinations of input and output admittances the following formulas can be derived

$$Y_{p1} = G_{p1} + sC_{p1} = G_{out1} + G_{inp3} + s(C_{out1} + C_{inp3}), \tag{13}$$

$$Y_{p2} = G_{p2} + sC_{p2} = G_{inp1} + G_{out2} + G_{out3} + s(C_{inp1} + C_{out2} + C_{out3}), \tag{14}$$

$$Y_{p3} = G_{p3} + sC_{p3} = G_{out1} + G_{inp2} + s(C_{out1} + C_{inp2}). \tag{15}$$

Each transfer function changes into

$$K_{LP}(s) = \frac{\dfrac{g_{m3}g_{m1}g_{m2}}{C_1C_2(G+Y_{p1})}}{D(s)}, \tag{16}$$

$$K_{BP}(s) = \frac{\dfrac{g_{m3}g_{m1}C_2 + g_{m3}g_{m1}Y_{p3}}{C_1C_2(G+Y_{p1})}s}{D(s)}, \tag{17}$$

$$K_{BR}(s) = \frac{\dfrac{g_{m3}}{G+Y_{p1}}s^2 + \dfrac{g_{m3}(C_1Y_{p3}+C_2Y_{p2})}{C_1C_2(G+Y_{p2})}s}{D(s)} + \frac{\dfrac{g_{m3}(g_{m1}g_{m2}+Y_{p2}Y_{p3})}{C_1C_2(G+Y_{p2})}}{D(s)}, \tag{18}$$

$$K_{HP}(s) = \frac{\dfrac{g_{m3}}{G+Y_{p1}}s^2 + \dfrac{g_{m3}(C_1Y_{p3}+C_2Y_{p2})}{C_1C_2(G+Y_{p1})}s}{D(s)} + \frac{\dfrac{g_{m3}(Y_{p2}Y_{p3})}{C_1C_2(G+Y_{p1})}}{D(s)}, \tag{19}$$

$$K_{AP}(s) = \frac{\dfrac{g_{m3}}{G+Y_{p1}}s^2 - \dfrac{g_{m3}(g_{m1}C_2+C_2Y_{p2}+C_1Y_{p3})}{C_1C_2(G+Y_{p1})}s}{D(s)} + \frac{\dfrac{g_{m3}(g_{m1}g_{m2}+g_{m1}Y_{p3}+Y_{p2}Y_{p3})}{C_1C_2(G+Y_{p1})}}{D(s)} \tag{20}$$

where the denominator can be expressed as

$$D(s) = a_2s^2 + a_1s + a_0, \tag{21}$$

and the coefficients are

$$a_2 = 1, \tag{22}$$

$$a_1 = \frac{g_{m1}g_{m3}C_2 + GC_2Y_{p2} + C_2Y_{p1}Y_{p2} + C_1GY_{p3} + C_1Y_{p1}Y_{p3}}{C_1C_2(G+Y_{p1})}, \tag{23}$$

$$a_0 = \frac{g_{m1}g_{m2}Y_{p1} + g_{m1}g_{m2}G + g_{m1}g_{m3}Y_{p3} + GY_{p2}Y_{p3}}{C_1C_2(G+Y_{p1})} + \frac{Y_{p1}Y_{p2}Y_{p3}}{C_1C_2(G+Y_{p1})}. \tag{24}$$

It is evident that these terms are quite complicated even if the parasitics are inside substitutions Y.

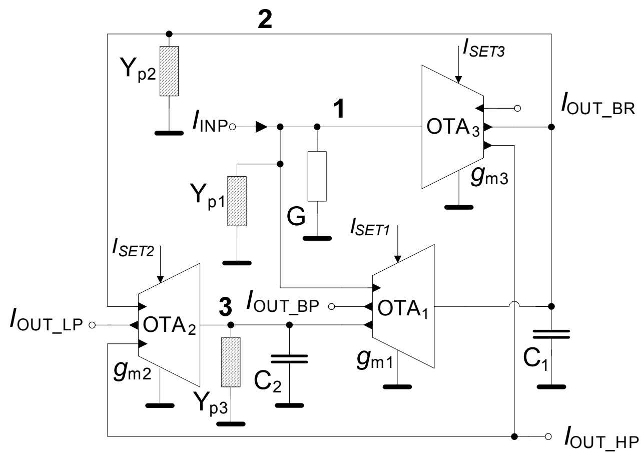

Fig. 17. Important parasitic admittances in the proposed structure.

More valuable insight into these problems brings study of the equations in Matlab together with the PSpice simulations where the final effects are visible directly on module characteristics. Capacitive element Y_{p1} given by C_{inp3} and C_{out1} introduces parasitic pole and subsequent usability of the filter in the high-frequency domain (see Fig. 18). The capacitive elements Y_{p2} composed of C_{inp1}+C_{out2}+C_{out3} and also Y_{p3} given by C_{out1} + C_{inp2} cause frequency shift f_C as it is illustrated in Fig. 19.

The effect of the resistive part of the admittance Y_{p1} is obvious in Fig. 20. Thanks to the low value of R ($R << 1/G_{p1}$) it is almost negligible. Only its value approaching hundreds of Ω can make similar changes as the change of Q using g_{m3} or R on purpose. The influence of the resistive part of Y_{p2} on frequency response is evident in Fig. 21. The main problem is that there is a significant drop of attenuation in the reject band of the BR filter for low values under 10 kΩ. Changes of Q are also visible.

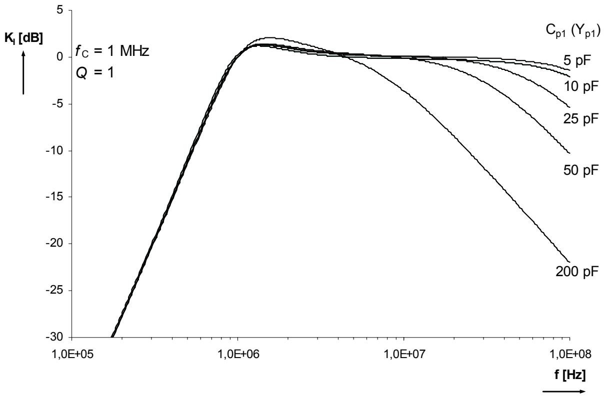

Fig. 18. Influences of $C_{p1} = C_{out1}+C_{inp3}$ (Y_{p1}).

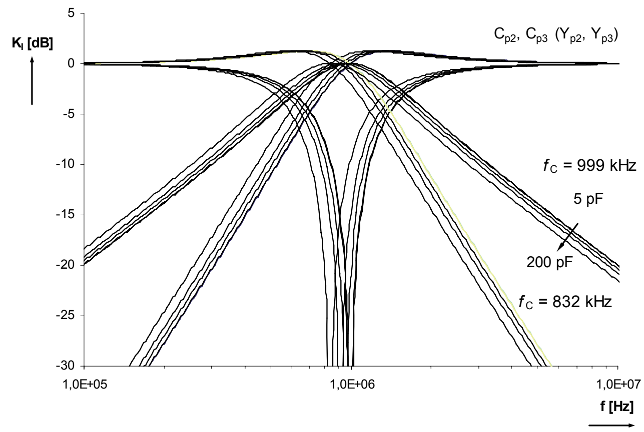

Fig. 19. Influences of C_{p2} and C_{p3}.

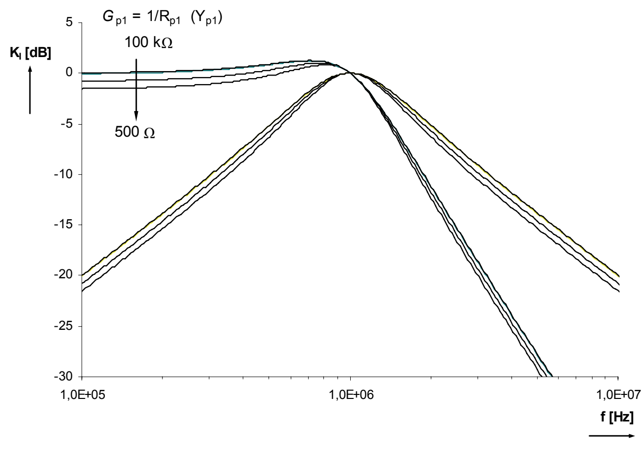

Fig. 20. Influences of $G_{p1} = G_{out1}+G_{inp3}$ (Y_{p1}).

Another interesting effect is lowering the resistance of the node 3 (Y_{p3}) as it is given in Fig. 22. This phenomenon is followed by a dramatic deformation of the frequency response, especially in the case of BP filter. Note that there is a finite attenuation in the reject band. Fundamental problem is if each OTA has this bad feature since these effects are cumulative. The influence of the output resistance on the HP filter frequency curve is given in Fig. 23. If the input resistance of each OTA is changed simultaneously its effect on f_C and Q is lower but still causes a finite attenuation in the reject band. This statement is confirmed via Fig. 24. It follows from the previous results that if input and output resistances of the used OTAs are bigger than tens of kΩ (CMOS technology allows much greater values) their effects are minimal. One can also conclude that a limited attenuation of HP and BP filters is dominantly affected by the values of G_{p2} and G_{p3}.

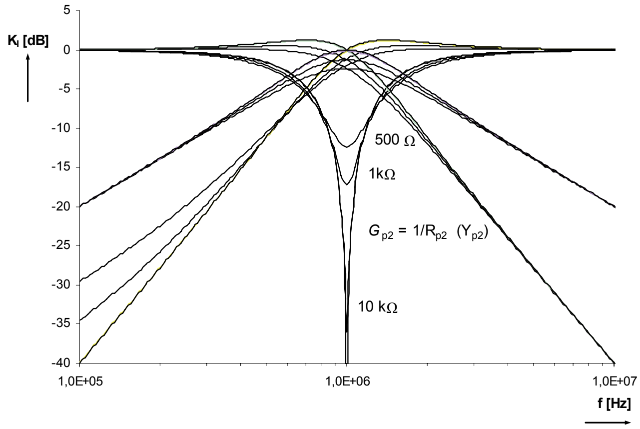

Fig. 21. Influences of $G_{p2} = G_{inp1}+G_{out2}+G_{out3}$ (Y_{p1}).

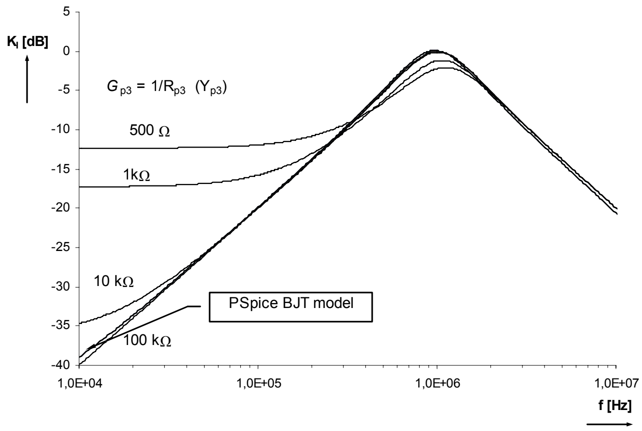

Fig. 22. Influences of $G_{p3} = G_{out1}+G_{inp2}$ (Y_{p3}).

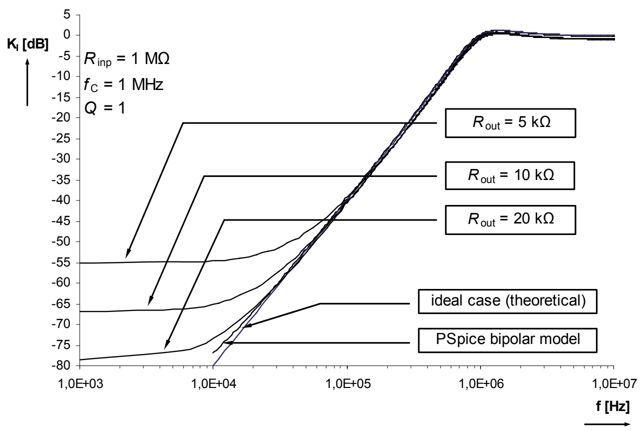

Fig. 23. Influences of R_{out} ($1/G_{out}$) all OTA simultaneously.

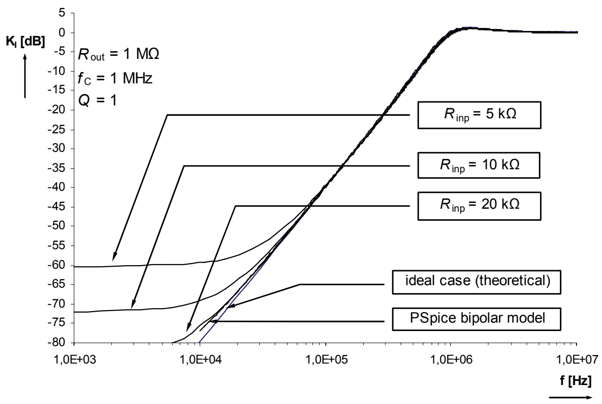

Fig. 24. Influences of R_{inp} ($1/G_{inp}$) all OTA simultaneously.

It turns out that the effects caused by the input and output resistances of OTAs are much more important than effects caused by the input and output capacitances. For working capacitances about units of pF the parasitics can shift f_C slightly but this can be compensated by controllable OTAs. Note that the parasitic capacitances can be added to the working ones which are designed to be large enough. Thus these parasitics need not be considered. For example there is 23 kHz offset relative to f_C designed to be 1 MHz for simulation using BJT models.

If only effects of parasitic resistors and capacitors acting at the same nodes as the working capacitors the equation for characteristic frequency and quality factor is

$$\omega_C^* = \sqrt{\frac{g_{m1}g_{m2}}{C_1C_2}} \cdot \sqrt{\frac{(g_{m1}(g_{m2}G_{p1}+g_{m2}G+g_{m3}G_{p3})+G_{p2}G_{p3}G+G_{p1}G_{p2}G_{p3})C_1C_2}{(C_2C_{p2}+C_1C_2+C_1C_{p3}+C_{p2}C_{p3})(G+G_{p1})g_{m1}g_{m2}}}\,, \tag{25}$$

$$Q^* = \frac{C_1G}{g_{m1}g_{m3}} \cdot \omega_C^* \cdot \frac{(G+G_{p1})(C_2C_{p2}+C_1C_2+C_1C_{p3}+C_{p2}C_{p3})g_{m1}g_{m3}}{((G+G_{p1})(C_{p2}G_{p3}+C_{p3}G_{p2}+C_2G_{p2}+C_1G_{p3})+(C_{p3}+C_2)g_{m1}g_{m3})C_1G}\,. \tag{26}$$

6. Experimental Verification

The universal filter circuit structure shown in Fig. 7 was measured with transconductors MAX 435 [30].

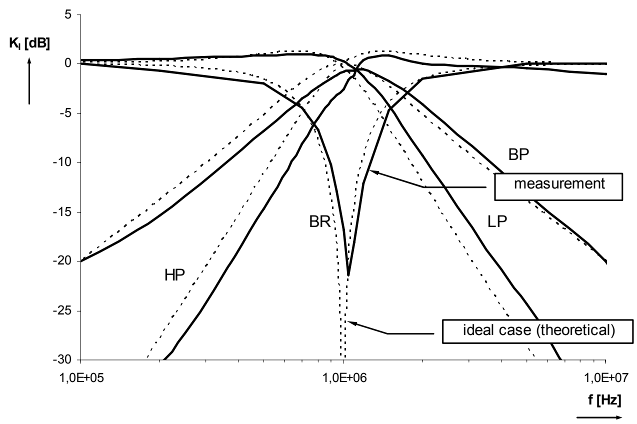

Fig. 25. Measured magnitude responses of the universal filter.

As suggested in the text for multiple OTA outputs inputs were connected to parallel. The measured magnitude responses are in Fig. 25, a short example of tuning of the LP filter is provided in Fig. 26 and adjusting of the BP response is in Fig. 27. Transient response of the BP filter is shown in Fig. 28.

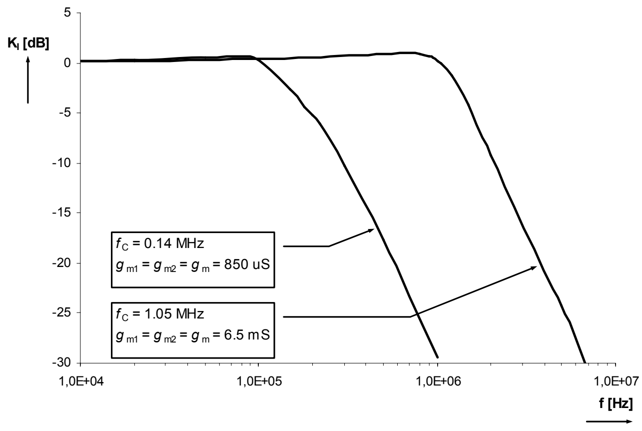

Fig. 26. Measured tuning of the LP filter.

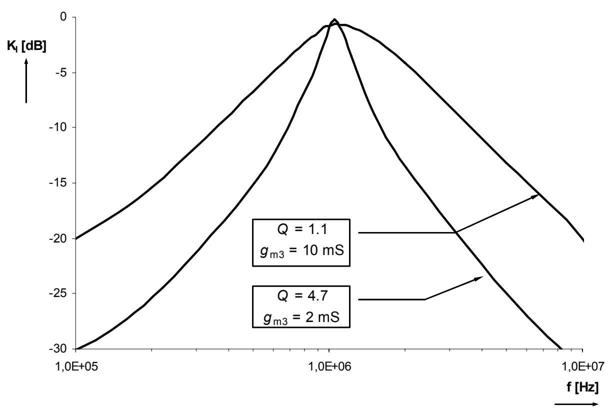

Fig. 27. Measured adjusting of the quality factor of the BP.

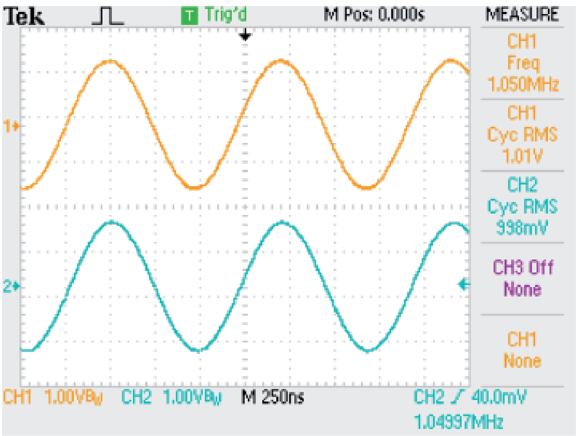

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Fig. 28. Transient response of the BP (f_C = 1.05 MHz), above is the input signal and below is the output signal.

7. Conclusion

In this paper the design of multifunctional biquad was presented employing OTAs with single input and three outputs as the active devices. For PSpice simulation models of OTAs on transistor level of abstraction with fast bipolar technology were used. Simple circuit structure (only three active and passive elements), easy electronic tuning of the cutoff frequency and possibility of adjusting of the BP filter bandwidth can be considered as main advantages of this multifunctional biquad. It is shown that three active blocks with three current outputs are sufficient for universal filtering circuit. Experimental results hinted that the filter is suitable for working in video band frequency range. Resistance *R* can be easy realized by OTA, so that realization of this structure in integrated form (IC-s) is possible. Mentioned results confirmed theoretical assumptions.

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