# FIRST–ORDER TRANSFER SECTIONS WITH RECONNECTION–LESS ELECTRONICALLY RECONFIGURABLE HIGH–PASS, ALL–PASS AND DIRECT TRANSFER CHARACTER

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Presented research introduces active filtering circuits which allow change of the transfer type without necessity of reconnection of the input or output terminal that can be very useful for on-chip applications. Our attention is focused on simple first-order filters that allow high-pass response (HP), all-pass response (AP) and also direct transfer (DT) with constant magnitude and phase characteristics between two terminals (input and output) by adjusting of one controllable parameter (current gain $B$ in our case). Useful modification of the well-known current follower transconductance amplifier (CFTA), the so-called Z-copy current-controlled current follower differential input transconductance amplifier (ZC-CCCFDITA) and adjustable current amplifier were utilized in these circuits. Interesting possibilities (crossing between several transfer functions) of presented circuits require different values of $B$ to obtain desired transfer function that is very important for practice and selection of specific way of control. Requirements on value of this continuously controllable gain $B$ differ among presented structures. Theory is supported by simulation and measurement results with behavioral models utilizing commercially available active elements and simulation results with active elements based on CMOS models.

K e y w o r d s: active filters, electronic control, reconfiguration, reconnection-less multifunction, Z-copy current-controlled current follower differential input transconductance amplifier, ZC-CCCFDITA

## 1 INTRODUCTION

Many suitable active elements for circuit synthesis of various applications have been presented in literature [1]. Some of them allow interesting features and give useful possibilities of electronic control in applications. However, their further modifications bring some additional advantages that are not available in their basic forms and definitions. These improvements mean additional implementation of controllable parameters in the active element in the most cases. We know four types of electronic control in frame of the active element. The first group utilizes controllable transconductance $(g_m)$ [1, 2]. The second group deals with controllable intrinsic resistance $(R_x)$ of the current input terminal (mainly in current-mode active elements) [3]. Control of current gain $(B)$ [4] becomes very popular in recent years mainly [5–11]. Utilization of the adjustable voltage gain $(A)$ is also very useful in many cases, but complexity of active elements is worse [12] than basic structures utilizing $g_m$ or $R_x$ control [2,3]. Design of active elements in combination of several (at least two) types of control in frame of one active element is one of today's trends [13–19].

We prepared overview of combined active elements employing current follower/inverter and transconductance subparts. Active elements combining current inverter and transconductance amplifier have been already investigated precisely. For example current inverter transconductance amplifier (CITA) and its modifications (using so-called Z-copy technique [20]) were reported in recent literature [21]. Active elements presented in previously discussed work have only one possibility of control by electronically adjustable transconductance.

We provided detailed comparison of the CFTA/CITA-based circuit structures (or their modifications) that provide first- and/or second- order transfer functions, to see recent progress in the field of CFTA/CITA-based first-order filters. Solutions discussed in [21–25] are simple first-order circuits. Some of them provide also universal [23] or multifunctional filtering characteristics [24]. Typical distinctiveness of the multifunctional/universal filters is the necessity of physical reconnection of the input or output terminal for change of the transfer type.

Change of the transfer function of the filter is quite important feature of applications on the chip. This feature is required if direct connection between two nodes

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**Table 1.** Comparison of the parameters of presented solutions to recently reported reconnection-less voltage-mode filtering structures based on other active elements

|  | Active elements (number) | Type of functions | Available transfer functions |
|---|---|---|---|
| [26] | ECCII- (1), VB (1) | biquadratic ($2^{nd}$ order) | AP, BR |
| [27] | ECCII- (4), MO-CF/I (2), VB (1) or OTA (5), VB (1) | biquadratic ($2^{nd}$ order) | AP, BR |
| [28] | OTA (2), ECCII-(1) | $1^{st}$ order | AP, LP, iDT |
| [29] | ZC-CG-VDCC (1) | $1^{st}$ order | AP, LP, iDT, DT |
| Fig. 3a | ZC-CCCFDITA (1), CA (1) | $1^{st}$ order | iHP, AP, iDT |
| Fig. 3b | ZC-CCCFDITA (1), CA (1) | $1^{st}$ order | HP, iAP, DT |

Abbreviations:

| | |
|---|---|
| ECCII- | Current Conveyor of Second Generation (negative) with possibility of gain adjusting between X and Z terminal |
| OTA | Operational Transconductance Amplifier |
| VB | Voltage Buffer |
| CA | Current Amplifier (adjustable gain B) |
| MO-CF/I | Multiple-output Current Follower/Inverter |
| ZC-CG-VDCC | Z-copy Controlled-Gain Voltage Differencing Current Conveyor |
| DT | direct transfer |
| iDT | inverted direct transfer |
| BR | band reject transfer function |
| AP | all-pass transfer function |
| iAP | inverting all-pass transfer function |
| LP | low-pass transfer function |
| HP | high-pass transfer function |
| iHP | inverting high-pass transfer function |

(in frame of the complex communication system — sub-blocks) have to be replaced by HP or other filter response in order to reject some type of wide-band or selective noise or distortion. It is necessary to provide reconnection of the output by switches, it practice. However, some types of the filter with specific features (reconnection-less reconfigurable) allow change of the transfer function by simple tuning of externally adjustable parameter [26] — no physical/electrical reconnection is necessary. Recently reported reconnection-less filtering circuits were summarized in Tab. 1 for easy comparison. Solution discussed in [26] allows change of the 2nd-order transfer function

between AP and BR by adjustable current gain. Solution of some drawbacks of [26] was discussed in full state variable follow the leader structure presented in [27]. However, circuit is quite complicated. The first order reconnection less filters were presented also in [28, 29]. Both realizations, are focused on reconfiguration between AP, LP and direct transfer (DT). Unfortunately, no realization reported in the past (Tab. 1) was focused on AP, HP and DT transfer functions that can be changed electronically. For more details see Tab. 1.

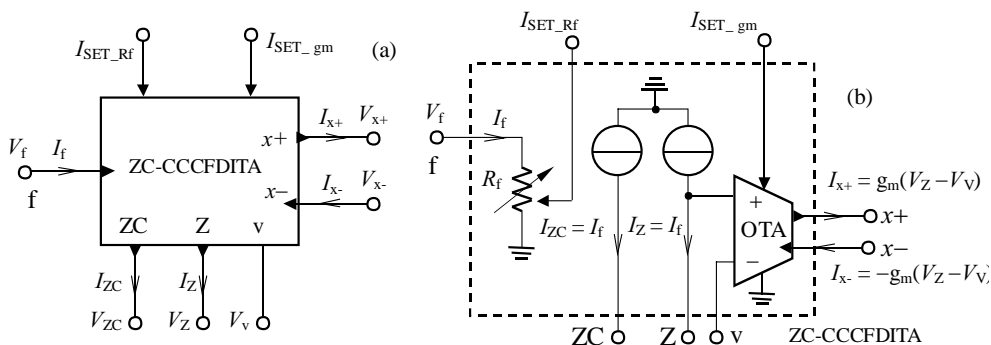This paper is focused on simple $1^{st}$-order circuits where additional adjustable current amplifier was en-



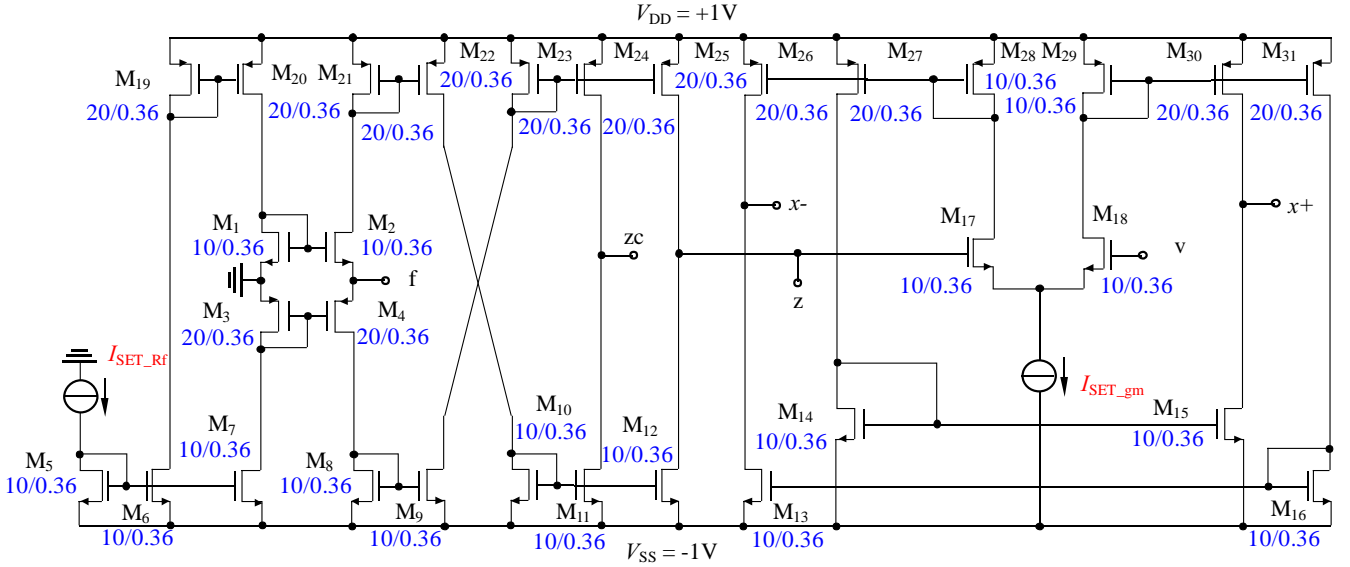**Fig. 1.** Principle of the ZC-CCCFDITA: (a) — symbol, (b) — behavioral model

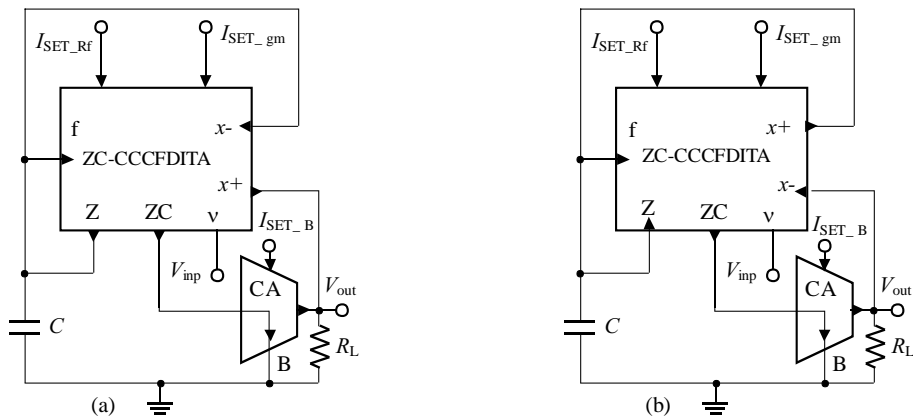**Fig. 2.** Possible internal CMOS topology of proposed ZC-CCCFDITA active element



**Fig. 3.** HP/AP structures utilizing single ZC-CCCFDTA and adjustable current amplifier: (a) — using non-inverting controllable current amplifier, (b) — using inverting current amplifier

gaged to obtain several types of transfer characteristics including direct connection (non-inverting or inverting) between input and output terminal (the same form of the numerator and denominator of the transfer function — transfer with constant magnitude and phase characteristic) in several very simple circuits.

The paper is organized as follows: Section 2 shows definition of presented modification of active element (so-called Z-copy current-controlled current follower differential input transconductance amplifier — ZC-CCCFDITA) and possible way of its CMOS implementation. Chapter 3 deals with 1st-order electronically reconfigurable transfers (HP, AP, DT) in simple circuits based on ZC-CCCFDITA and adjustable current amplifier with minimal number of passive elements and their theoretical analysis. Section 4 introduces method of implementation of the ZC-CCCFDITA by commercially available active elements (behavioral model) and its application in selected type of the reconfigurable filtering solution to-

gether with CMOS implementation. Comparison of ideal and simulated results with CMOS and behavioral model is also presented. Exemplary experimental results are given in Section 5. Summarization of achieved features, requirements and results is provided in conclusion.

## 2 Z–COPY CURRENT–CONTROLLED CURRENT FOLLOWER DIFFERENTIAL INPUT TRANSCONDUCTNACE AMPLIFIER

The Z-copy current-controlled current follower differential input transconductance amplifier (ZC-CCCFDITA) belongs to family of modern active elements [1] deeply investigated by Herencsar *et al*, [30]. Principle of this useful modification of basic CFTA is in controllable input intrinsic resistance $R_f$, transconductance ($g_m$) of the output section and additional differential voltage input [25] of the output (transconductance section – OTA). Basic CFTA does not use fully-differential input of the OTA
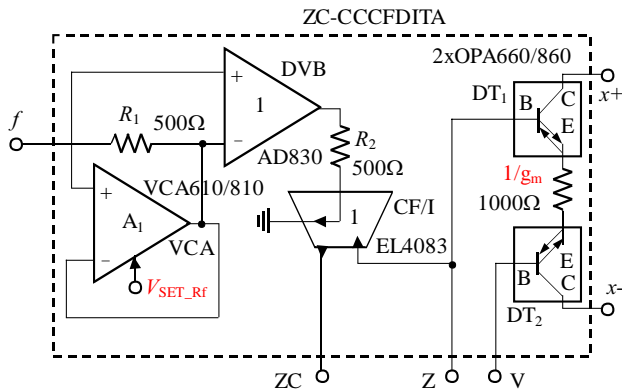
**Fig. 4.** Behavioral model of the ZC-CCCFDITA employing commercially available active devices

section (one input terminal is grounded) [1], however, it seems to be advantageous. Principal conception of the ZC-CCCFDITA is shown in Fig. 1.

Input current $I_f$ is mirrored to two output terminals of the first section (current follower). One current output is connected directly to the second (output) section based on operational transconductance amplifier (OTA) and called $z$. The second auxiliary current output of the first section is identical copy of the input current $I_f$, this output is called $zc$. Negative input of the OTA section is lead out of the device and noted as $v$. Two current outputs of the OTA section have both polarities or we can use multiple-output OTA section. Principle is clear from Fig. 1b. The CMOS structure utilizing current controlled current conveyor of second generation [3] connected as multiple-output current follower and dual-output OTA section [2, 22] is shown in Fig. 2.

Controllable intrinsic resistance is given by [31, 32]

$$R_f = \frac{1}{\sqrt{I_{\text{SET\_Rf}} K_{\text{Pn}} \frac{W_{M1,2}}{L_{M1,2}}} + \sqrt{I_{\text{SET\_Rf}} K_{\text{Pp}} \frac{W_{M3,4}}{L_{M3,4}}}}, \quad (1)$$

and transconductance of the output OTA section has known expression [31]

$$g_m = 2\sqrt{I_{\text{SET\_gm}} K_{\text{Pn}} \frac{W_{M17,18}}{L_{M17,18}}} \quad (2)$$

where constant 2 is given by gain of current mirrors (P-MOS: $M_{28}$–$M_{27}$ and $M_{29}$–$M_{30}$) and $K_{Pn,p}$ are technological constants ($\mu_0 C_{ox}$) of used fabrication technology [33] (TSMC 0.18 μm).

## 3 FIRST–ORDER FILTERS WITH ELECTRONICALLY RECONFIGURABLE TYPE OF THE TRANSFER FUNCTION

Almost all active electronic systems are integrated on chip today. Electronic adjustability of the systems is important for control of bandwidth, pole frequency, oscillation frequency, quality factor, *etc*. However, extensive

reconfiguration like change of the transfer function of the frequency filter is not possible because it requires change of topology, reconnection of input/output nodes (SIMO, MISO types) very often. Unfortunately, after fabrication no change of the internal structures is possible. We present simple 1st-order transfer functions that are available in advanced circuitry as HP or AP response without necessity of changing the topology or reconnection of nodes (SISO — single input and single output type). Only electronically adjustable parameter is used for change type of the transfer function. Therefore this way can be very useful for on-chip subsystems. We will demonstrate principle on two solutions both are practically the same but different configurations of polarities of the outputs of active elements give us significantly different possibilities.

Circuit in Fig. 3a is HP/AP filter and DT based on ZC-CCCFDITA and Adjustable Current Amplifier. It has both of the $z$ and $zc$ terminals with positive polarity. Transfer function has form

$$K_1(s) = \frac{g_m R_L}{R_f} \frac{B - sCR_f}{g_m + sC}. \quad (3)$$

The circuit structure behaves as inverting HP (iHP) section for $B = 0$. AP section is available for $B = 1$ for a condition $g_m = 1/R_f$. Inverting direct transfer (iDT) is set by $B = -1$. Zero and pole frequencies are given by $\omega_z = B/R_fC$ and $\omega_p = g_m/C$.

Independent control of the zero and pole location (outside pure AP behavior) is possible also by $R_f$ and $g_m$ (bilinear filter). However, both parameters influence passband gain.

The second solution of the filter has the same circuit solution but direction (polarity) of output currents from outputs and auxiliary terminal $z$ are opposite, see Fig. 3b. This difference is important for type (polarity) and value of controllable current gain $B$. Despite the fact that both circuits have the same structure, transfer function of the solution in Fig. 3b is slightly different

$$K_2(s) = \frac{g_m R_L}{R_f} \frac{2 - B + sCR_f}{g_m + sC}, \quad (4)$$

where $B = 1$ gives DT response (constant unity magnitude and phase equal to 0 degrees) if $g_m = 1/R_f$. The transfer function of HP response is obtained in case of $B = 2$ and the inverting AP (iAP) response is available for $B = 3$ $(g_m = 1/R_f)$. Zero frequency is given by $\omega_z = (2 - B)/R_fC$ and pole frequency is the same as in the previous case $(\omega_p = g_m/C)$.

The first case (Fig. 3a) requires controllable parameter $B \geq 0$ for change of the transfer type from HP to AP response, the second case (Fig. 3b) allows change also from HP to AP, but for $B \geq 2$. Migration of zero from left to the right side of the complex space is conditioned by both polarities of $B$ $(B = \pm 1)$ in the first case in Fig. 3a, which is sophisticated task for current amplifier. Fortunately, solution in Fig. 3b allows migration of zero just
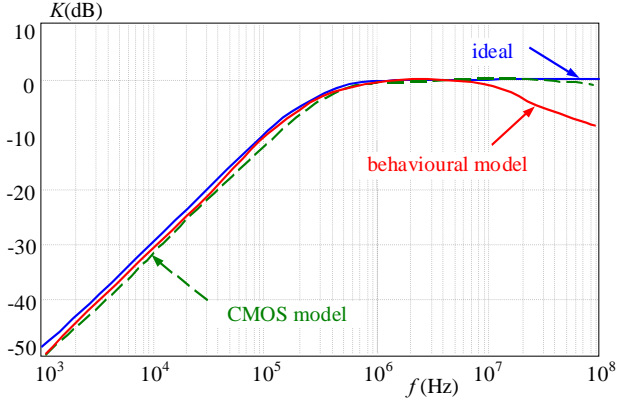
**Fig. 5.** HP magnitude response obtained from structure utilizing behavioral or CMOS model of ZC-CCCFDITA and adjustable current amplifier
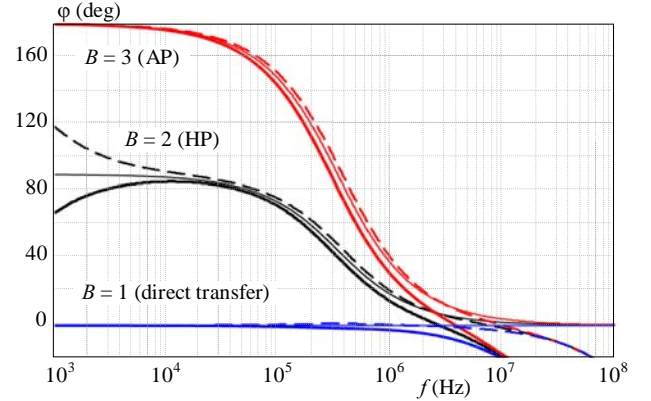


**Fig. 6.** AP and DT magnitude responses obtained from structure utilizing behavioral and CMOS models of ZC-CCCFDITA and adjustable current amplifier
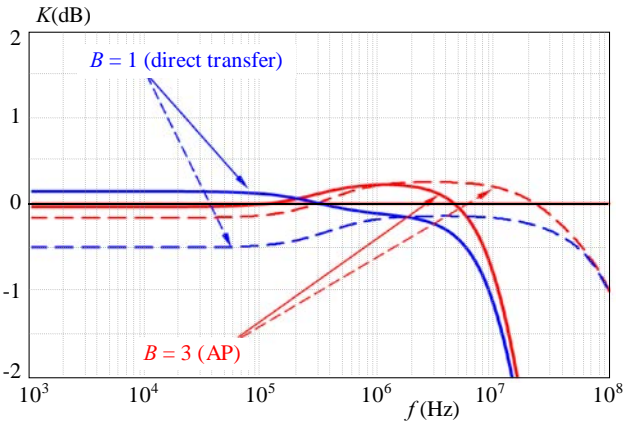


**Fig. 7.** All phase responses obtained from structure utilizing behavioral and CMOS models of ZC-CCCFDITA and adjustable current amplifier (three discrete current gains)

in one polarity of the $B$. Necessity of higher gain $B = 3$ (for AP response) is small disadvantage of this solution (higher gain = higher power consumption in many cases). Both circuits are suitable for cascading (high-impedance input terminal). This solution will be analyzed in more details in Chapter 4.

## 4 SIMULATION RESULTS

### 4.1 Simulation of the selected filtering solution

Circuit in Fig. 3b was chosen for detailed study. Its features are interesting for investigation because it allows HP, AP and DT functions simultaneously in one circuit structure (without reconnection) only by change of parameter $B$ (in one polarity). The rest of parameters was selected as: $R_f = R_L = 1\,\text{k}\Omega$, $C = 470\,\text{pF}$, $g_m = 1\,\text{mS}$. Current amplifier constructed from EL2082 [35] was used for control of loop-gain and type of the transfer (commercially available devices-based behavioral model).

We prepared the following behavioral model (Fig. 4) of the ZC-CCCFDITA based on commercially available devices (VCA610/810 [36], AD830 [37], EL4083 [38],

EL2082 [35] and diamond transistor OPA860 [39, 40]). Supply voltage of the behavioral model was ±5 V. Discussed model employs controllable current amplifier/ follower part that allows voltage control of the $R_f$ based on voltage controllable amplifier (VCA) (method firstly proposed in [41]). The resistance $R_f$ is given by [41] as

$$R_{\text{f}} = R_1\big(1 + 10^{-2(V_{\text{SET\_Rf}}+1)}\big). \tag{5}$$

Differential voltage amplifier (DVB) can be easily replaced by the second VCA to control also the current gain [41]. Resistor $R_2$ serves as voltage/current converter. Transconductance section is utilized by two diamond transistors (DTs).
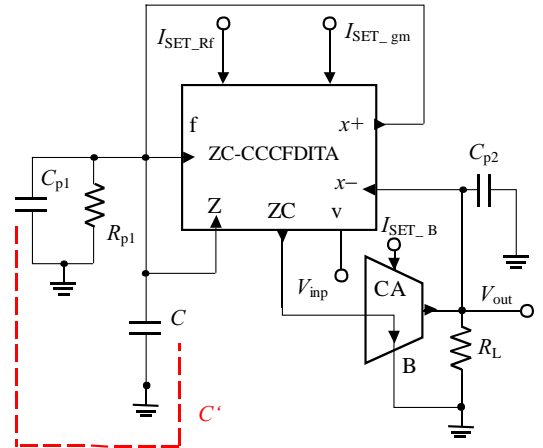


**Fig. 8.** Model representing the most important parasitic influences in circuit from Fig. 3b

CMOS structure from Fig. 2 was also used (after appropriate changes of polarities of the outputs and auxiliary terminals in accordance to Fig. 3b) for simulation together with CMOS current amplifier based on section used also in [11, 12] and [29] especially for example. Its current gain [34] is given by

$$B = \frac{NI_{\text{b2}}}{2I_{\text{set\_B}}} \cong \frac{I_{\text{b2}}}{I_{\text{set\_B}}}. \tag{6}$$
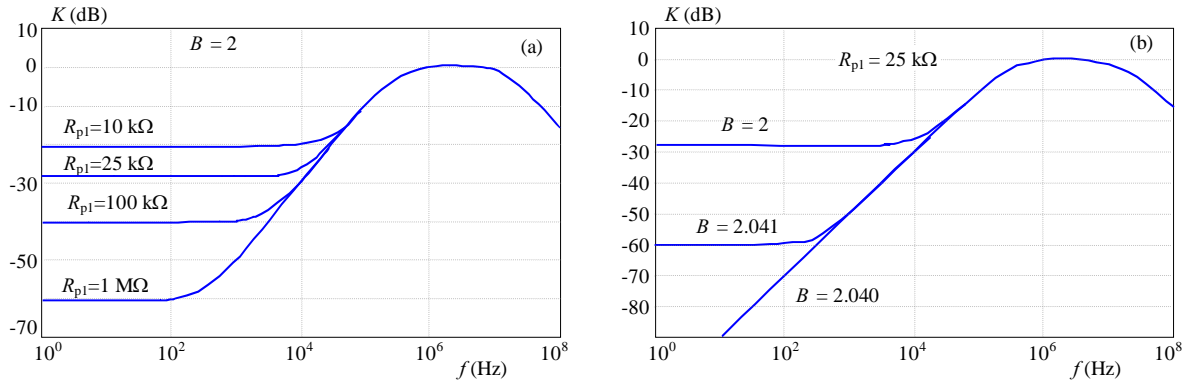
**Fig. 9.** HP response behavior under conditions of parasitic elements: (a) — stepping of $R_{p1}$ while $B$ is constant, (b) — stepping of $B$ while $R_{p1}$ is constant

Figure 5 shows magnitude HP response for three traces: ideal ($f_{\mathrm{p}} = 339$ kHz for $B = 2$, $g_{\mathrm{m}} = 1$ mS, $R_{\mathrm{f}} = 1$ kΩ), simulation with behavioural model ($f_{\mathrm{p}} = 296$ kHz for $V_{\mathrm{SET\_B}} = 2.46$ V, $g_{\mathrm{m}} = 1$ mS, $V_{\mathrm{SET\_Rf}} = 1$ V) and simulation with CMOS model ($f_{\mathrm{p}} = 378$ kHz for $I_{\mathrm{SET\_B}} = 56.5$ μA, $I_{\mathrm{SET\_gm}} = 54$ μA $I_{\mathrm{SET\_Rf}} = 34$ μA) using the ZC-CCCFDITA device. Figure 6 indicates reconfigurability between AP, HP and direct transfer in phase response. There ideal traces, simulation results with behavioural model and simulation results with CMOS model of the ZC-CCCFDITA are compared. The ideal trace, behavioural model and CMOS model responses are distinguished by style of the line (ideal trace - thin solid line, behavioural model thick line, CMOS model thick dashed line). Sets of parameters (in order to obtain AP for ideal $B = 3$, HP for ideal $B = 2$ and direct transfer for ideal $B = 1$) are following: AP (behavioural model - $f_{\mathrm{p}} = 292$ kHz, $V_{\mathrm{SET\_B}} = 4$ V, $g_{\mathrm{m}} = 1$ mS, $V_{\mathrm{SET\_Rf}} = 1$ V; CMOS model - $f_{\mathrm{p}} = 373$ kHz, $I_{\mathrm{SET\_B}} = 35$ μA$S$, $I_{\mathrm{SET\_gm}} = 54$ μA, $I_{\mathrm{SET\_Rf}} = 34$ μA), HP (behavioural model - $f_{\mathrm{3dB}} = 296$ kHz, $V_{\mathrm{SET\_B}} = 2.46$ V, $g_{\mathrm{m}} = 1$ mS, $V_{\mathrm{SET\_Rf}} = 1$ V; CMOS model - $f_{\mathrm{3dB}} = 378$ kHz, $I_{\mathrm{SET\_B}} = 56.5$ μA, $I_{\mathrm{SET\_gm}} = 54$ μA, $I_{\mathrm{SET\_Rf}} = 34$ μA), direct transfer (behavioural model - $V_{\mathrm{SET\_B}} = 1.15$ V, $g_m = 1$ mS, $V_{\mathrm{SET\_Rf}} = 1$ V; CMOS model - $I_{\mathrm{SET\_B}} = 81$ μA; $I_{\mathrm{SET\_gm}} = 54$ μA; $I_{\mathrm{SET\_Rf}} = 34$ μ A). Magnitude responses for DT and HP configuration are given in Fig. 7. Sets of parameters is the same as note above (for AP and DT). Supply voltage was always ±5 V for behavioural model and ±1 V for CMOS model.

### 4.2 Parasitic analysis of selected filtering solution

We provided detailed analysis of important parasitic influences in the selected structure (Fig. 3b). Main problems create additional impedance in high-impedance node of working capacitor and parasitic capacitance in node of working resistor $R_{\mathrm{L}}$ (in parallel). Model representing these problems is depicted in Fig. 8. We suppose following simplifications, because they are nearly always fulfilled: $R_{\mathrm{ZC}} \gg R_{\mathrm{inpCA}}$, $R_{x-} \gg R_{\mathrm{L}}$ therefore, we can

suppose $R_{\mathrm{L}}$ in node operating as only dominant resistance. Parasitic elements are estimated (determined from behavioral model in Fig. 4 for example) as follows: $R_{p1} \approx R_{\mathrm{f}}\|R_z\|R_{x+} \approx R_{\mathrm{f}}\|25\,\mathrm{k\Omega}$, $C_{p1} \approx C_{\mathrm{f}} + C_z + C_{x+} \approx 10$ pF, $C_{p2} \approx C_{\mathrm{out\_CA}} + C_{x-} \approx 10$ pF. We used also simplification $C' = C + C_{p1}$. The rest of parameters was used as in case of Section 4.1. Low value of $R_{x\pm}$ (25 kΩ [39, 40]) seems to be the most important problem for us. Approximate equation for overall transfer function of the filter has form in this case

$$K_2'(s) = g_{\mathrm{m}}R_{\mathrm{L}}\big(R_{p1}(2 - B) + R_f + sC'R_{\mathrm{f}}R_{p1}\big)\big/\big(g_{\mathrm{m}}R_{\mathrm{f}}R_{p1}$$
$$+ R_{\mathrm{f}} + s\left[R_{\mathrm{f}}R_{p1}C' + R_{\mathrm{L}}C_{p2}(g_{\mathrm{m}}R_{\mathrm{f}}R_{p1} + 2R_{p1} + R_{\mathrm{f}})\right]$$
$$+ s^2 C' C_{p2} R_f R_{p1} R_L\big). \quad (7)$$

Simulation results of the HP response (that is the most influenced by parasitic behavior) we have shown in Fig. 9. Of course $R_{p1}$ has direct impact on zero location and value of finite attenuation in the stop band, see Fig. 9a.

Ideal value $B = 2$ is expected for pure HP response without zero. Existence of real $R_{p1}$ causes unintentional creation of zero also for $B = 2$. However, problem of low $R_{x\pm}$ (the most important contributor of $R_{p1}$) can be still easily solved by $B$ control (as we suppose to utilize for reconfiguration) to compensate impact of $R_{p1}$ and to obtain pure HP again (for $B = 2.04$), see Fig. 9b.

Second order denominator of influenced transfer function has also impact on pass-band transfer drop at higher frequencies (but maybe lower than available bandwidth of active elements in some cases) that is visible in all transfer responses (HP, iAP, DT). Estimation of this pole frequency can be provided from: $\omega_{p2} \cong 1/R_{\mathrm{L}}C_{p2} \cong 16$ MHz.

## 5 EXPERIMENTAL RESULTS

We measured discussed type of the filter (Fig. 3b) based on behavioral model from Fig. 4 and additional current amplifier (EL2082) under the same conditions as described in Section 4. Measurements were provided by network vector analyzer ENA E5071C. Brief exemplary results of the filter configurations, particularly HP, iAP
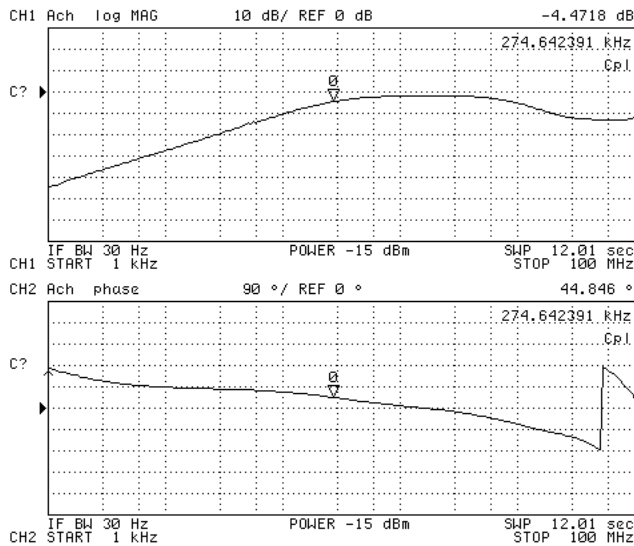
**Fig. 10.** Measured magnitude and phase response of HP configuration, $V_{\text{set\_B}} = 2.6$ V
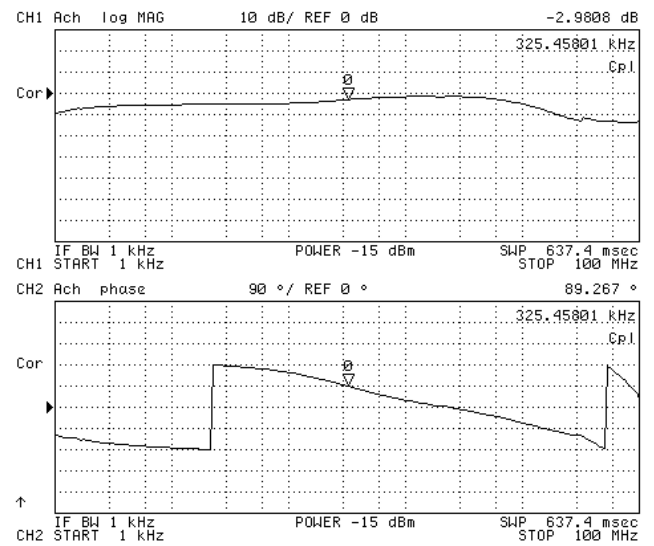


**Fig. 11.** Measured magnitude and phase response of iAP configuration, $V_{\text{set\_B}} = 4.3$ V
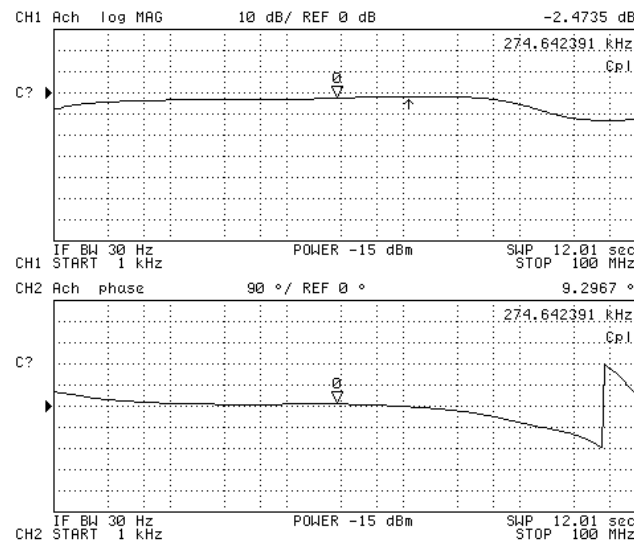


**Fig. 12.** Measured magnitude and phase response of DT configuration, $V_{\text{set\_B}} = 1$ V

and DT transfers, are shown in Figs. 10–12. Experimental results are close to expectations and behavior of simulated case.

## Acknowledgement

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