

# Z-Copy Controlled-Gain Voltage Differencing Current Conveyor: Advanced Possibilities in Direct Electronic Control of First-Order Filter

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**Abstract**—A modified version of voltage differencing current conveyor (VDCC) and its performance in detail is presented in this paper. Modified VDCC, so-called z-copy controlled gain voltage differencing current conveyor (ZC-CG-VDCC), offers interesting features from adjustability point of view. The active element allows independent electronic control of three adjustable parameters: intrinsic resistance of current input terminal, transconductance and current gain of the output stage which is not possible in case of conventional VDCC. The characteristics of proposed CMOS implementation designed using TSMC LO EPI 0.18  $\mu$ m technology process parameters are shown and discussed. Simple application in reconfigurable reconnection-less first-order voltage-mode multifunctional filter is shown and verified by SPICE simulations and experimentally. The filter tuning and change of the transfer function type is allowed by the controllable parameters of the ZC-CG-VDCC.

**Index Terms**—Electronic control, current conveyor, current gain, first order, intrinsic resistance, multifunctional filter, reconfiguration, transconductance, voltage differencing current conveyor, voltage-mode, z-copy, ZC-CG-VDCC.

## I. INTRODUCTION

Active elements [1] with more than one controllable parameter are very important for technical progress in this field, because they allow more effective electronic control,

increasing variability in applications, simple circuit design and simple circuit structure. Frequently discussed active elements use principles based on electronic control of the intrinsic resistance ( $R_x$ ) of the current input terminal  $x$  [2] (in the frame of current conveyor [3]) and control of the transconductance section ( $g_m$ ) [4]. Active elements with possibility of current gain ( $B$ ) control were presented by Surakamponporn et al. [5] and Fabre et al. [6]. However, only the current gain control is realized.

Some active elements that combine two externally controllable parameters (by bias voltage or current) were already discussed in applications of analog circuits and systems [7]–[9]. Minaei et al. [7] proposed current conveyor with adjustable properties i.e. adjustable  $B$  between  $x$  and  $z$  terminals and adjustable intrinsic resistance of the current input terminal  $x$ . Marcellis et al. [8] introduced modified conveyor with controllable features of voltage gain between  $y$  a  $x$  and current gain between  $x$  and  $z$  terminals. Kummern et al. [9] also combined  $R_x$  and  $B$  control in their version of translinear current conveyor.

Several combined active elements, based on transconductance section (OTA) [1], [4] and current conveyor of second generation (CCII) [2], [3], were already proposed. Typical examples of active elements with two-parameter control are some modifications of the very known current differencing transconductance amplifier (CDTA) [1], [10], where  $R_x$  and  $g_m$  control is implemented by DC bias currents [11], [12]. For example, the current conveyor transconductance amplifier (CCTA) [1], [13] also utilizes independent  $R_x$  and  $g_m$  control in some of its modifications [14]. One modification of CCTA [15] also employs current gain control, where current conveyor with gain-adjustable properties was used. Controllable current gain in frame of current conveyor [5], [6] seems to be an interesting and

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valuable advantage. Active elements having this advantage attained many innovative modifications [16], [17].

The main aim of this paper is a design of an enhanced active element with useful and feasible controllable features. A voltage differencing current conveyor (VDCC) belongs to family of novel hybrid elements presented by Biolek et al. [1]. In this contribution the VDCC, used as main core of the proposed new active device, is presented as  $z$ -copy variant with controllable parameters. We refer this modification as  $z$ -copy controlled gain voltage differencing current conveyor (ZC-CG-VDCC). Hitherto published works have already discussed so-called differential voltage current conveyor (DVCC) [1], [18]–[21]. Nevertheless, both elements (VDCC and DVCC) have different behaviour and also different block structure that inheres from basic behaviour. The DVCC has two differential voltage input terminals  $y$  and realizes difference of two voltages [18]–[21]. The rest of the conception is identical to common current conveyor [2], [3]. One current input terminal  $x$  and current output terminal  $z$  (or multiple terminals  $\pm z$ ) are available. In comparison to discussed DVCC, the VDCC also consists of transconductance section (OTA) [1], [4] and offers additional auxiliary terminal for more universality of such element. Very interesting active elements, which belong to this family, were also proposed by Soliman [22] under designation pseudo-differential current conveyors (PDCCs). For example, the CCTA [13]–[15] utilizes same types of sub-blocks (CCII and OTA) as VDCC, however in reverse order of interconnection. This different order of interconnection also brings interesting features in applications. However, any of above discussed active elements and approaches do not allow control of three parameters within the frame of one active device as is presented in this paper. This approach allows construction of very simple applications with minimum number of passive elements.

## II. Z-COPY CONTROLLED-GAIN VOLTAGE DIFFERENCING CURRENT CONVEYOR

Proposed active element, so-called  $z$ -copy controlled gain voltage differencing current conveyor (ZC-CG-VDCC) is shown in Fig. 1. This element was derived from basic theoretical concept of VDCC [1]. The conventional VDCC consist of a transconductance amplifier [1], [4] connected to the  $y$  terminal of classical second generation current conveyor [3]. Important fact is that only transconductance control is available in frame of conventional VDCC. Our modification allows simultaneous and mutually independent control of three important parameters, i.e.  $g_m$ ,  $R_x$  of current input terminal  $x$  in frame of the CCII section [2], and also  $B$  between  $x$  and  $z$  terminals of the CCII section [5]–[9]. Behavioural model consists of the transconductor OTA-DISO (differential input and single output) and electronically controllable CCII (ECCII) [5]–[7], [9]. The OTA section allows  $g_m$  control and ECCII section realizes control of  $R_x$  and  $B$ .

Symbol of ZC-CG-VDCC in Fig. 1(a) utilizes high impedance voltage differencing inputs  $p$ ,  $n$ , auxiliary terminals  $\pm z_{TA}$ ,  $z_{cTA}$  (outputs of transconductance

section), high impedance positive and negative current outputs of section of current conveyors  $z_p$ ,  $z_n$ , low-impedance current input / voltage output  $x$  (current conveyor part) and three terminals for external control of  $B$ , intrinsic resistance, and transconductance by bias currents. Following equations describe inter-terminal relations:  $V_x = V_{z_{TA}} + R_x I_x$ ,  $I_{z_{TA}} = -I_{z_{TA}} = I_{z_{cTA}} = (V_p - V_n)g_m$ ,  $I_{z_p} = I_x B$ ,  $I_{z_n} = -I_x B$ .

Figure 1(b) explains behaviour of the proposed device in details and its possible block diagram is given in Fig. 1(c). Such active element seems to be complex, but internal CMOS topology is not challenging, see Fig. 2. Basic block structure form Fig. 1(c) was taken into account for design of CMOS realization in Fig. 2. There are three important parts (transconductor, current conveyor of second generation and adjustable current amplifier). The first part is the transconductance amplifier [1], [4], [23] with differential NMOS pair connected to a voltage input of CMOS current conveyor. Intrinsic resistance control was performed in frame of the current conveyor section [2], [23], which is separated from the last block forming adjustable current amplifier [24]. The reason for this subdivision is simple. Bias control of intrinsic resistance in frame of current conveyor with current amplifier section influences at least dependence of current gain on control bias current significantly as was discussed in [25]. Therefore, independent current conveyor and independent bias current serves for intrinsic resistance controlling purposes.

The transconductance of the OTA section is given by ideal equation [23]

$$g_m = 2\sqrt{I_{set\_gm} K_{Pn} \frac{W_{M1,2}}{L_{M1,2}}}, \quad (1)$$

where constant 2 is given by current mirror gain (see Fig. 2). Intrinsic resistance of current input  $x$  has expression [23]

$$R_x = \frac{1}{\sqrt{I_{set\_Rx} K_{Pn} \frac{W_{M11,12}}{L_{M11,12}}} + \sqrt{I_{set\_Rx} K_{Pp} \frac{W_{M13,14}}{L_{M13,14}}}}, \quad (2)$$

and adjustable current gain has form [24]

$$B = \frac{NI_{b2}}{2I_{set\_B}} \cong \frac{I_{b2}}{I_{set\_B}}, \quad (3)$$

where  $N=2$  (see Fig. 2). Proposed CMOS model was simulated and analysed with TSMC LO EPI 0.18  $\mu\text{m}$  technology process parameters [26], where fabrication constants (given by gate-oxide capacitance and mobility of carriers) have approximate values of  $K_{Pn} = 170.4 \mu\text{A}/\text{V}^2$  and  $K_{Pp} = 35.7 \mu\text{A}/\text{V}^2$ .

## III. SPICE SIMULATION RESULTS OF THE ZC-CG-VDCC

Main parameters of the proposed ZC-CG-VDCC with power supply voltages  $\pm 1$  V are given in following figures. Gain control of current from  $x$  to  $z$  terminals was verified by adjusting of bias current  $I_{set\_B}$  from 20  $\mu\text{A}$  to 100  $\mu\text{A}$  in range of  $B$  from 3.76 to 0.36 (Fig. 3).

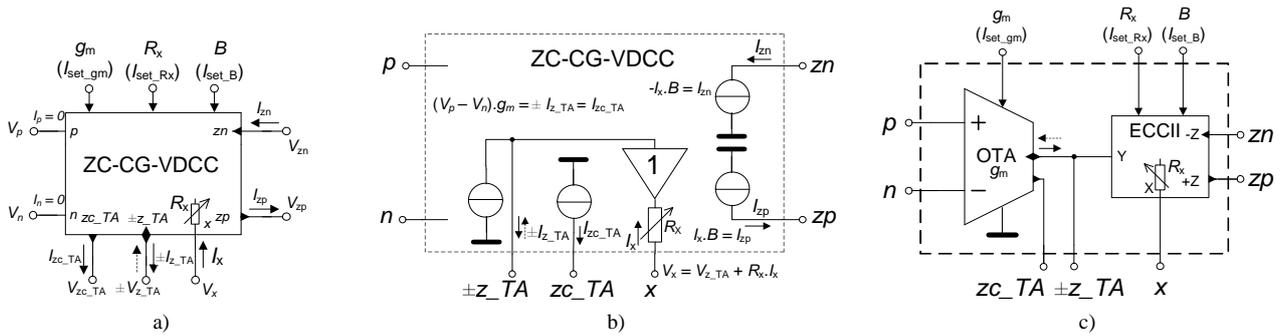


Fig. 1. Proposed ZC-CG-VDCC with independent control of three parameters: a) symbol, b) behavioral model, c) possible block conception.

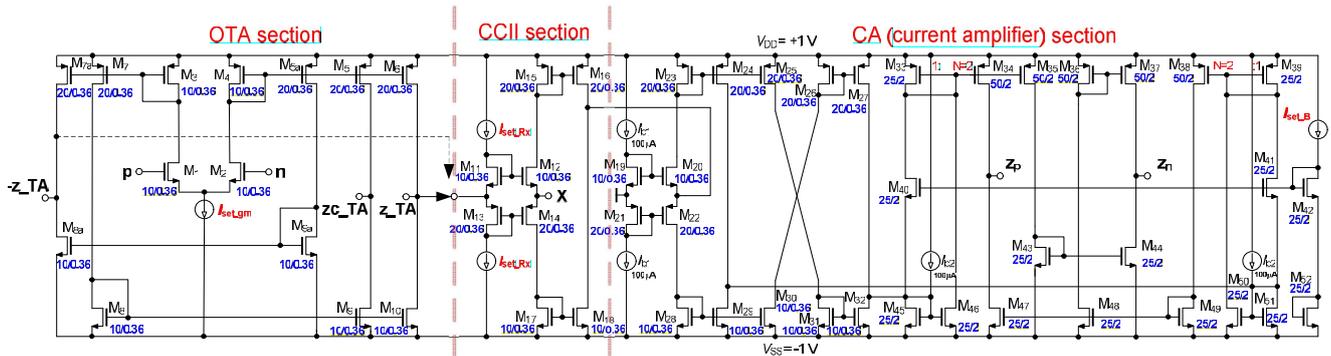


Fig. 2. CMOS realization of proposed ZC-CG-VDCC.

Selected transfers for  $B = 3, 2, 1, 0.5$  are shown in Fig. 3 (DC transfer characteristic and frequency response).

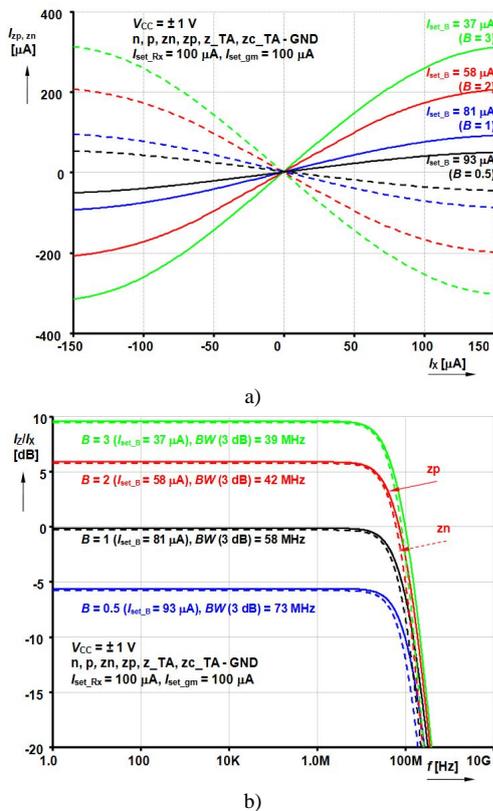


Fig. 3. Transfer characteristics of controlled current amplification for selected values of gain: a) DC transfers, b) AC frequency responses.

Linear dynamical range of input current ( $I_x$ ) is almost  $\pm 100 \mu A$  and bandwidth 39 MHz for  $B = 3$ . The second important adjustable parameter of presented active element

is transconductance. Bias control of  $I_{set\_gm}$  from  $10 \mu A$  to  $150 \mu A$  allows changes of  $g_m$  from  $255 \mu S$  to  $1919 \mu S$ . Dynamical range of  $V_p$  is approximately  $\pm 100$  mV and bandwidth 505 MHz for  $g_m = 1.5$  mS. Characteristics in DC and AC domain are shown in Fig. 4 in detail for three selected values (0.5, 1.0 and 1.5 mS) of  $g_m$ . DC characteristic of voltage gain between  $z\_TA$  and  $x$  port is shown in Fig. 5(a).

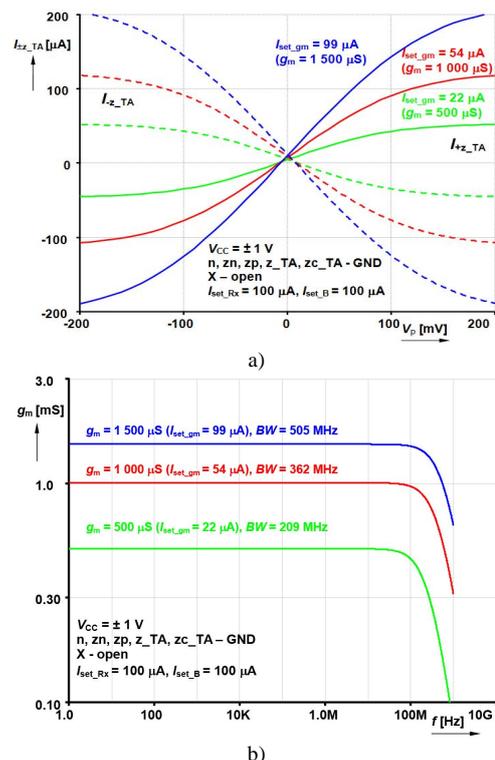


Fig. 4. Transconductance characteristics for selected values of  $g_m$ : a) DC transfers, b) AC frequency responses.

Figure 5(b) shows dependence of  $R_x$  on  $I_{set\_RX}$ . Input resistance is controllable from 2.53 k $\Omega$  to 451  $\Omega$  by  $I_{set\_RX}$  adjusted from 10 to 150  $\mu$ A. Important parameters of the proposed ZC-CG-VDCC model are summarized in Table I. Notes in Fig. 3–Fig. 5 mean information for connection of remaining terminals for presented set of analyses.

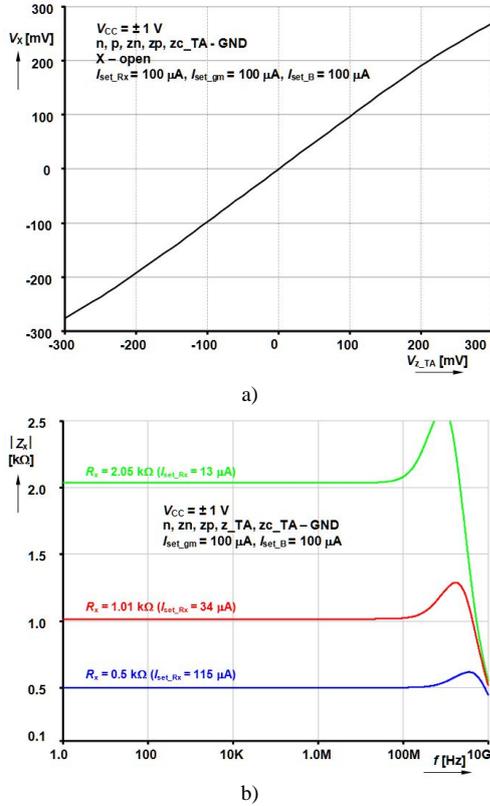


Fig. 5. Important characteristics of the current conveyor part ( $R_x$  terminal): a) DC transfer between  $z\_TA$  and  $x$  terminal, b) dependence of  $R_x$  on  $I_{set\_RX}$ .

#### IV. APPLICATION EXAMPLE:

##### RECONFIGURABLE FIRST-ORDER MULTIFUNCTION FILTER

Controllable features of proposed active device can be used in so-called reconfigurable reconnection-less tunable multifunctional filter (no change of output or input terminal or change of structure is required for change of the transfer function [27] – electronic control allows contactless reconfiguration) very beneficially. These solutions were not studied in detail in the past and our initial experience shows that such active elements like ZC-CG-VDCC with variety of controllable possibilities are very useful for their synthesis.

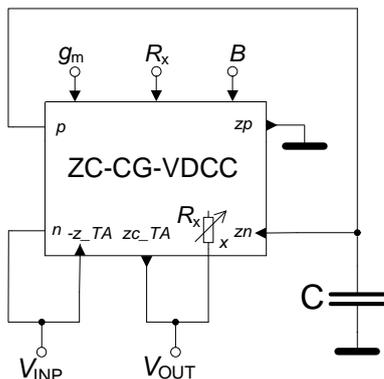


Fig. 6. Reconnection-less reconfigurable and tunable low-pass and all-pass filter.

Proposed solution is shown in Fig. 6. Note that circuit in Fig. 6 requires  $z\_TA$  terminal with opposite (negative) polarity. It is indicated by dashed line in CMOS structure in Fig. 2. Transfer function (TF) of the circuit in Fig. 6 has form

$$K(s) = \frac{V_{OUT}}{V_{INP}} = \frac{Bg_m - sC(R_x g_m - 1)}{Bg_m + sC}, \quad (4)$$

where zero and pole frequencies ( $f_z$ ,  $f_p$ ) are given as:  $\tilde{S}_z = Bg_m/(C(R_x g_m - 1))$  and  $\tilde{S}_p = Bg_m/C$ . It is clearly seen that current gain  $B$  serves for simultaneous control of  $f_{p,z}$ . The  $R_x$  configures type of the transfer function electronically independently on other parameters. The all-pass (AP) filter response is available in case when  $g_m R_x = 2$  and its TF has a form

$$K_{AP}(s) = \frac{V_{OUT}}{V_{INP}} = \frac{Bg_m - sC}{Bg_m + sC}, \quad (5)$$

TABLE I. SUMMARIZATION OF IMPORTANT FEATURES OF THE ZC-CG-VDCC CMOS MODEL.

Controllable parameters	
parameter	tested range of adjusting
current gain ( $B$ [-])	0.36 – 3.76 ( $I_{set\_B} = 100 \mu\text{A} - 20 \mu\text{A}$ )
transconductance ( $g_m$ [ $\mu\text{S}$ ])	255 – 1 919 ( $I_{set\_gm} = 10 \mu\text{A} - 150 \mu\text{A}$ )
intrinsic resistance ( $R_x$ [ $\text{k}\Omega$ ])	2.53 – 0.451 ( $I_{set\_Rx} = 10 \mu\text{A} - 150 \mu\text{A}$ )
DC performances ( $I_{set\_gm} = I_{set\_Rx} = I_{set\_B} = 100 \mu\text{A}$ ). TF analysis	
parameter	value
$I_{zp}/I_x$ [-]	0.36
$I_{zn}/I_x$ [-]	0.35
$I_{z\_TA}/V_p$ ( $g_m$ ) [ $\mu\text{S}$ ]	1 517
$V_{z\_TA}/V_x$ [-]	0.98
$R_{p,n}$ [ $\Omega$ ]	1E20
$R_{z\_TA, zc\_TA}$ [ $\text{k}\Omega$ ]	34.6
$R_x$ [ $\Omega$ ]	533
$R_{zp}$ [ $\text{k}\Omega$ ]	55.0
$R_{zn}$ [ $\text{k}\Omega$ ]	53.1
AC performances ( $I_{set\_gm} = I_{set\_Rx} = I_{set\_B} = 100 \mu\text{A}$ )	
parameter	value
$R_{z\_TA}(R_{zc\_TA})$ [ $\text{k}\Omega$ ]	> 35 for $I_{set\_gm} = 100 \mu\text{A}$ ( $f < 10$ MHz)
$R_{zp}, R_{zn}$ [ $\text{k}\Omega$ ]	> 50 for $I_{set\_B} = 100 \mu\text{A}$ ( $f < 1$ MHz)
$C_{p,n}$ [fF]	30
$C_{z\_TA}, C_{zc\_TA}$ [fF]	110
$C_{zp}$ [fF]	120
$C_{zn}$ [fF]	190

And if  $g_m R_x = 1$ , the low-pass (LP) filter response is obtained

$$K_{LP}(s) = \frac{V_{OUT}}{V_{INP}} = \frac{Bg_m}{Bg_m + sC}. \quad (6)$$

Special type of TF so-called inverting direct transfer (iDT) is available for  $g_m R_x = 2$  and  $B = 0$ . In these conditions the circuit works as direct connection (constant magnitude and phase response) between input and output terminal. Pure direct transfer (non-inverting) is available for  $g_m R_x \rightarrow 0$  together with any value of positive gain  $B$ .

We provided simulations of the circuit in Fig. 6 with proposed CMOS model (Fig. 2) and experimental verifications with behavioural model of ZC-CG-VDCC based on commercially available devices called diamond transistor (DT) OPA860 and multiplier EL2082 (ECCII-), see Fig. 7. Results presented in further text were gained for

$C = 470$  pF and  $g_m = 1$  mS, see comments in figures (figure captions) for obtained values and setting of parameters in simulations and experiments. Supply voltage of the behavioural model was  $\pm 5$  V ( $\pm 1$  V for CMOS model).

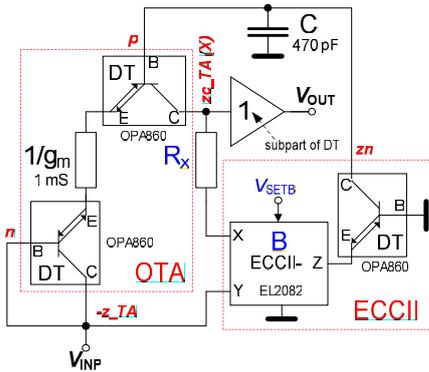


Fig. 7. Behavioral model of the ZC-CG-VDCC in proposed reconfigurable filtering application employing commercially available active devices.

Frequency responses of the TF change between AP, LP, DT and iDT were recorded by network analyser E5071C ( $f_{min} = 9$  kHz,  $P_{inp} = -15$  dBm/50  $\Omega$ ), see Fig. 8–Fig. 11.

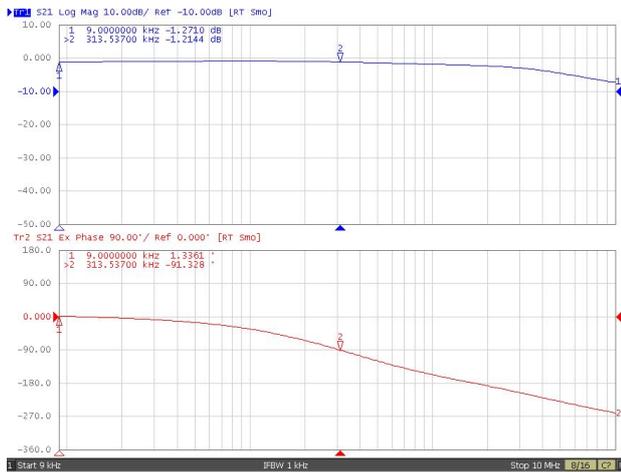


Fig. 8. All-pass filter response for  $g_m = 1$  mS,  $R_x = 2$  k $\Omega$  and  $B = 1$ .

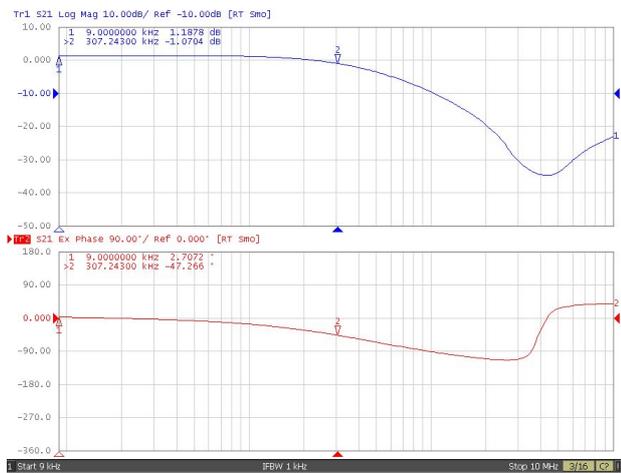


Fig. 9. Low-pass filter response for  $g_m = 1$  mS,  $R_x = 1$  k $\Omega$  and  $B = 1$ .

Phase responses in Fig. 12 document electronic reconfiguration between iDT, DT transfer and LP and AP response for specific set of  $R_x$  and  $B$  values, see details in Fig. 12 where also comparison of ideal, simulated (proposed CMOS model of the ZC-CG-VDCC) and measured

(behavioural model) traces is given. Validity of the behavioural model is supposed approximately to 1 MHz. Features of the CMOS model ( $R_x$ ,  $B$ ) do not allow operation of the filter (Fig. 6) in iDT and DT regime.

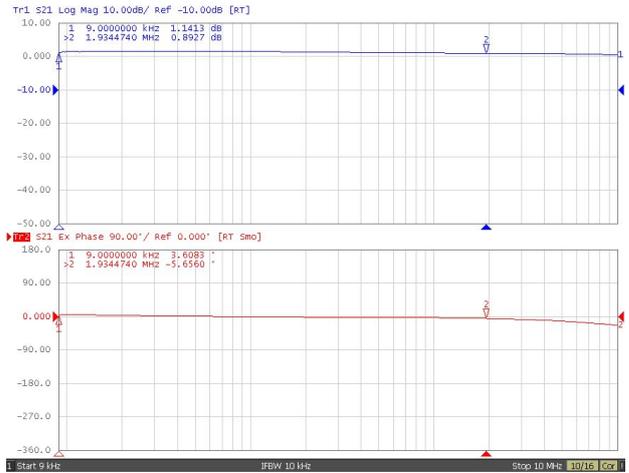


Fig. 10. Direct transfer response for  $g_m = 1$  mS,  $R_x = 0$  k $\Omega$  and  $B = 1$ .

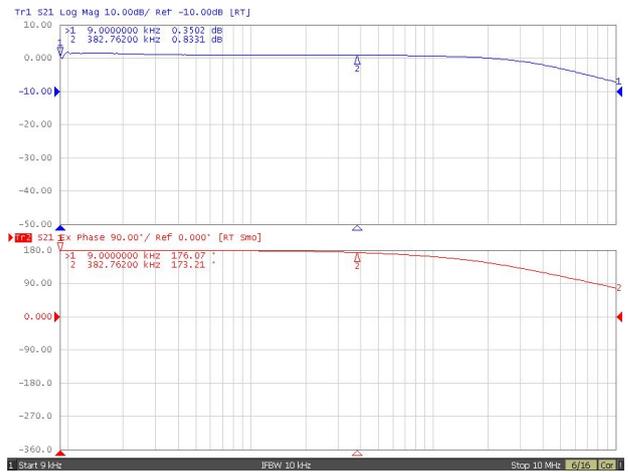


Fig. 11. Inverting direct transfer response ( $g_m = 1$  mS,  $R_x = 2$  k $\Omega$  and  $B = 0$ ).

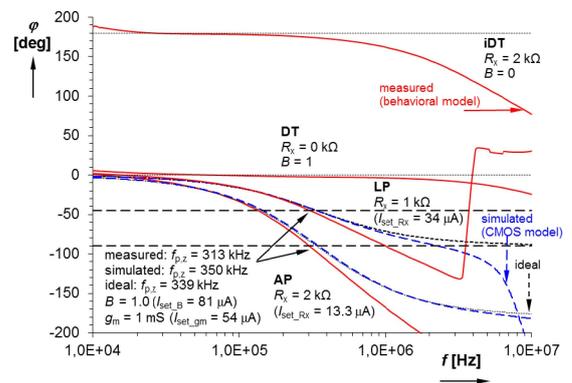


Fig. 12. Reconfiguration between iDT, DT, LP and AP (phase responses).

Transient response (oscilloscope Rigol DS1204B) of the AP filter is shown in Fig. 13 ( $f_{inp} = 313$  kHz, AP has the same setting as we give in caption of Fig. 8). Tuning features for AP and LP responses are shown in Fig. 14 and Fig. 15. Ideal values of pole/zero frequencies ( $f_{p,z}$ ) are 169, 339 and 667 kHz ( $B = 0.5, 1, 2$ ). Values of  $f_{p,z}$ , obtained from simulations were 187 kHz, 350 kHz and 696 kHz and experiments yield values 166 kHz, 313 kHz and 610 kHz

(see also Fig. 14).

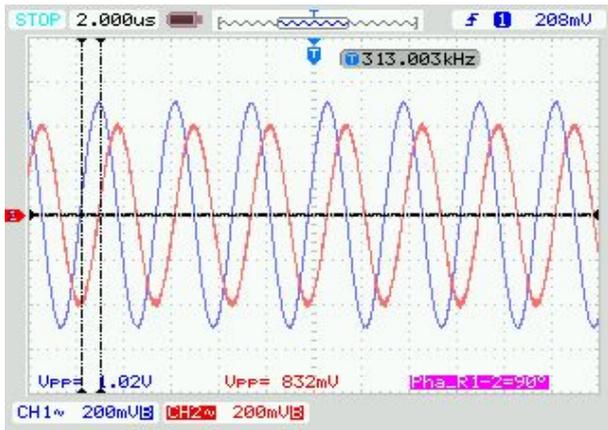


Fig. 13. Transient response of the AP filter for  $f_{in} = 313$  kHz ( $g_m = 1$  mS,  $R_x = 2$  k $\Omega$  and  $B = 1$ ).

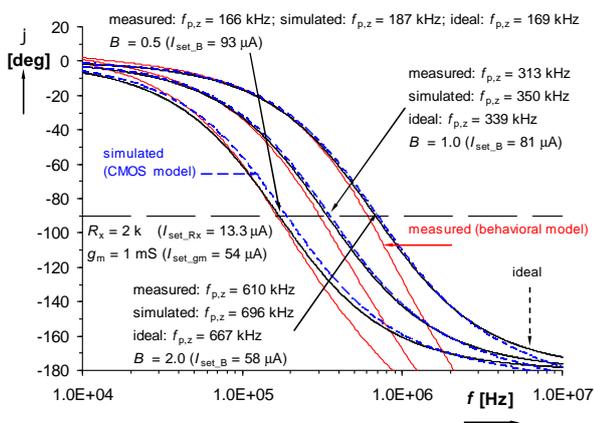


Fig. 14. Tuning of the AP filter (phase responses).

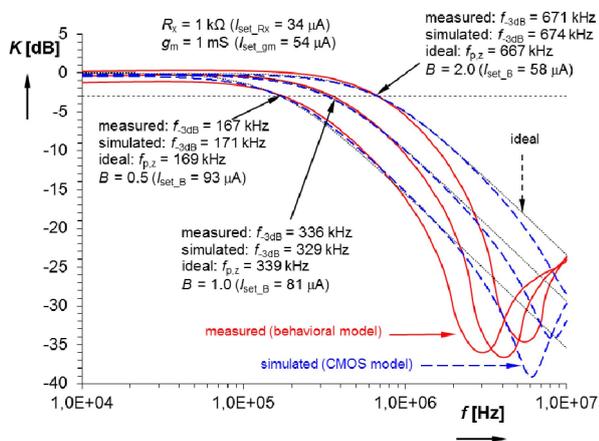


Fig. 15. Tuning of the LP filter (magnitude responses).

## V. CONCLUSIONS

Our work is focused on design of modification of the voltage differencing current conveyor, proposal of its model and example of its useful features in simple application. The most important advantages of proposed active element are availability of three types of independent electronic control and useful z-copy technique. Range of the  $B$  control of the CMOS model was verified between 0.36 and 3.76 ( $I_{set,B}$  from 100  $\mu$ A to 20  $\mu$ A), control of the  $g_m$  value between 255  $\mu$ S and 1 919  $\mu$ S ( $I_{set,gm}$  from 10  $\mu$ A to 150  $\mu$ A) and  $R_x$  value in range from 2.53 k $\Omega$  to 0.451 k $\Omega$  ( $I_{set,Rx}$  from 10  $\mu$ A to 150  $\mu$ A). Frequency features allow operation of CMOS

simulation model to tens of MHz. Bandwidth (3 dB) of the ZC-CG-VDCC model is determined by current amplifier block, where minimal value 39 MHz was obtained for  $B = 3$ , see Fig. 3(b). Further details are summarized in Table I. Proposed active element was implemented in simple electronically reconfigurable reconnection-less first-order multifunctional filtering structure working in voltage-mode which features were verified in frequency band of hundreds of kHz by Spice simulations and experimentally with behavioural model of the proposed active device employing commercially available devices. Electronic control allows change of the transfer type (direct transfer, inverting direct transfer, all-pass and low-pass response) and tuning of the  $f_{p,z}$  frequency (even independent control of  $f_z$ ). Tuning was tested for three values of  $B$  (0.5, 1, 2) that results in simulated  $f_{p,z}$  (187, 350, 696 kHz). Measurements provide 166 kHz, 313 kHz and 610 kHz (Fig. 14). Behavioural and CMOS models of the ZC-CG-VDCC represent expected behaviour of filtering application and confirm our assumptions. ZC-CG-VDCC seems to be interesting choice for circuit synthesis and possible fabrication.

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