Voltage Differencing Current Conveyor Differential Input Transconductance Amplifier: Novel Active Element and Its Resistorless Filtering Application

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Abstract— **This paper introduces novel modification of active element based on current conveyor transconductance amplifier core abbreviated as current controlled voltage differencing current conveyor differential input transconductance amplifier (CC-VDCCDITA). The active element is implemented by recently developed and manufactured IC modular device based on I3T25 0.35 µm ON Semiconductor CMOS process. Active element uses three internal active cells of this IC device for construction of the CC-VDCCDITA. An application example of proposed element in simple special resistor-less electronically adjustable biquadratic filter is shown. Brief comparison with state-of-the-art solutions indicates beneficial features of proposed solution. Simulation results in Cadence IC tool accompany precise laboratory experimental measurements with real prototype.**

Keywords—active element; biquad filter; current conveyor transconductance amplifier; electronic control; modular approach

I. INTRODUCTION

The development of modern active devices reached significant attention in recent years. Many interesting concepts were introduced in literature [1], [2]. Common trend in this type of development supposes interconnection of modular blocks representing active sub-circuit (multiterminal active device) of specific type (current conveyor, operational transconductance amplifier, operational amplifier, voltage buffers, etc.). These sub-circuits (the suitable designation of sub-circuit is cells in IC terminology) provide electronically controllable parameters in many cases in order to achieve multiparametric adjustability of the device. Unfortunately, majority of these modern approaches is based on hypothetical concepts only (the device has never been practically designed ever fabricated) supported by simulation results with some uncomplete and basic technological models of active circuitries providing results that are not realistic (omitted influences of bonding, PCB, wires, loading capacities, etc.). Typical solutions were collected and described for example in [2].

This work introduces real experimental results of circuitry with fabricated CMOS device tested in intended application, not only simulation results with doubtful/inaccurate models. The active device belongs to family of so-called current conveyor transconductance amplifier (CCTA) firstly developed by Prokop et al. [3], [4] as non-adjustable devices connecting current conveyor (CCII) [1], [2] and operational transconductance amplifier (OTA) [1], [2] elements together. It brings many advantageous features for circuit synthesis [5], [6]. Several modifications (in the view of number of terminals and electronically adjustable features – significant degree of freedom) has been reported in recent years [5]-[11]. These generations of modifications include implementation of controlled current gain [7], non-adjustable additional voltage input operations [8], [9] and non-adjustable additional current input operations [10]. Nevertheless, to the best of authors' knowledge, improvements (adjustable additional voltage input operations) of CCTA defined in this paper, have not been reported in literature.

This paper includes definition of active device (Section II), application example (special biquad filter) shown in Section III, and comparison of experimental (measured) laboratory results with Cadence IC tool simulations shown in Section IV. Section V brings short comparison of features of presented biquad filter with similar concepts known from literature and Section VII concludes this paper.

II. ACTIVE DEVICE PROPOSAL

Modular approach of the active device building [3], [4] has been used also in our case. We developed complex IC designed in 0.35 µm ON Semiconductor I3T25 CMOS process where several building cells are available [11]. These cells include controlled current conveyor of second generation (CCCII), voltage multipliers based on bipolar and unipolar multiplying core (MLTs), voltage-mode differential difference buffer (VDDB) and current amplifier. The full analysis and parameters of used cells can be found in [11]. Three of these cells (two multipliers and one CCCII) can be interconnected and implemented as newly defined active device shown in Fig. 1 and called as current controlled voltage differencing current conveyor differential input transconductance amplifier

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(CC-VDCCDITA). The device can be described by the following small-signal interterminal relations (inner terminals of cells and outer terminals of CC-VDCCDITA are distinguished by asterisk): $I_{Za*} = \pm(V_{p*} - V_{n*})\cdot g_{m1}$, $V_{X*} = V_{Za*} + R_X I_{X*}$, $I_{Zb*} = I_{X*}$, $I_{O*} = \pm(V_{Zb*} - V_{v*})\cdot g_{m2}$, $V_{p*} = V_{n*} = 0$. The input resistance of the X terminal (CCCII) can be electronically controlled by DC current I_{set_RX} as: $R_X \cong 3.5\cdot I_{set\_RX}^{-0.5}$. The transconductances of MLT-based operational transconductance amplifiers (g_m-s) are defined as $g_{m1} \cong 1.3\cdot10^{-3}\cdot V_{set\_gm1}$, $g_{m2} \cong 4.9\cdot10^{-3}\cdot V_{set\_gm2}$. The first value is valid for CMOS version, second for BJT version of MLT, see [11] for details. OTA is quite standard active element, however, in our case, the polarity of g_m can be easily changed by the polarity of $V_{set\_gm1,2}$. It is significant benefit for specific applications. This is also documented in Fig. 1 by bidirectional arrow of the $MLT_{1,2}$ outputs.

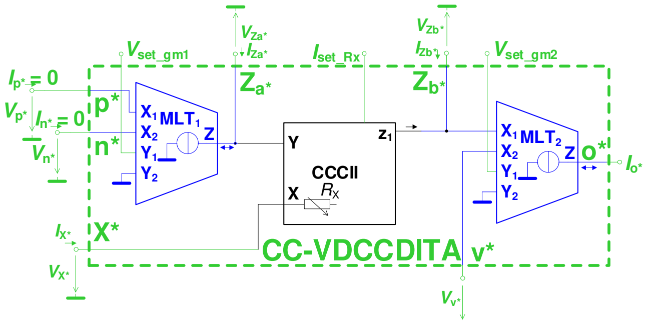


Fig. 1. Interconnection of internal cells in order to obtain CC-VDCCDITA active element.

III. TRANSADMITTANCE BIQUAD FILTER ALLOWING VARIABLE PASS-BAND GAIN WHEN TUNED

The biquadratic filter operating in so-called transadmittance mode is defined by $T(s) = I_{out}(s)/V_{inp}(s)$. Figure 2 shows two designed filtering topologies. In both cases, it consists of single CC-VDCCDITA element and two grounded capacitors. Transfer function for low-pass (LP) filter (Fig. 2a) is:

$$T_{LP}(s) = \frac{I_{out}}{V_{inp}} = \frac{\dfrac{g_{m1}g_{m2}}{C_1C_2R_X}}{s^2 + \dfrac{g_{m2}}{C_2}s + \dfrac{g_{m1}}{C_1C_2R_X}}, \tag{1}$$

Transfer response in case of band-pass (BP) filter (Fig. 2b) is:

$$T_{BP}(s) = \frac{I_{out}}{V_{inp}} = \frac{\dfrac{g_{m1}}{C_1R_X}s}{s^2 + \dfrac{g_{m2}}{C_2}s + \dfrac{g_{m1}}{C_1C_2R_X}}. \tag{2}$$

Pole frequency (ω_p), quality factor (Q) and bandwidth (BW) of both the filters are as follows:

$$\omega_p = \sqrt{\frac{g_{m1}}{C_1C_2R_X}} \cong \sqrt{\frac{4.8\cdot10^{-3}V_{set\_gm1}}{C_1C_2\cdot3.5\cdot\left(I_{set\_RX}\right)^{-0.5}}}, \tag{3}$$

$$\begin{aligned} Q &= \frac{1}{g_{m2}}\sqrt{\frac{g_{m1}}{R_X}\frac{C_2}{C_1}} \cong \\ &\cong \frac{1}{1.3\cdot10^{-3}V_{set\_gm2}}\sqrt{\frac{4.8\cdot10^{-3}V_{set\_gm1}}{3.5\cdot\left(I_{set\_RX}\right)^{-0.5}}\frac{C_2}{C_1}}, \end{aligned} \tag{4}$$

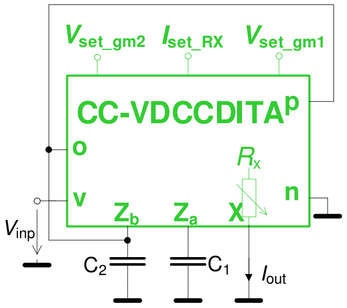
$$BW = \frac{g_{m2}}{C_2} \cong \frac{1.3\cdot10^{-3}V_{set\_gm2}}{C_2}. \tag{5}$$

Note that Q can be controlled by g_{m2} without disturbing ω_p. The influence of g_{m1} and R_X on pass-band gain of BP can be turned into benefit when this behavior is welcomed (some adaptive reacting circuits [12] for equalizing of the output response reacting on variable amplitude of input spectral components [12], [13]). The pass-band gain of BP is defined as:

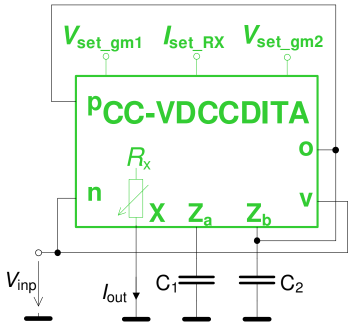
$$\begin{aligned} T_{0(\max)}\left(\omega_p\right) &= \frac{g_{m1}}{g_{m2}}\cdot\frac{1}{R_X} \cong \\ &\cong \frac{4.8\cdot10^{-3}V_{set\_gm1}}{1.3\cdot10^{-3}V_{set\_gm2}}\cdot\frac{1}{3.5\cdot\left(I_{set\_RX}\right)^{-0.5}}. \end{aligned} \tag{6}$$

The suitable parameters for tuning of the center frequency f_p and pass-band gain ($T_{0(\max)}$) at center frequency are g_{m1} and R_X simultaneously. All parameters can be adjusted electronically by DC bias current and DC voltages. The pass-band gain of the LP filter (1) can be found as: $T_0(\omega\to0) = g_{m2} \cong 1.3\cdot10^{-3}\cdot V_{set\_gm2}$.

Some signals have complicated behavior in time and frequency response. So-called adaptive filtering circuits are defined for these purposes [12]. However very complex control systems including peak detection, adjustable amplifiers, etc. and their precise setting are sometimes required [13]. Is some cases it may be helpful when their cut-off or center frequency is tuned and pass band gain varies in dependence on certain trend (dependence of gain on driving force). This case can be interesting at band-pass response when amplitude of tuned input signal increases with frequency and band-pass filter has to follow these changes and compensate these effects (in order to obtain output response completely flat over several frequency bands but still filtered and with certain bandwidth).



a)



b)

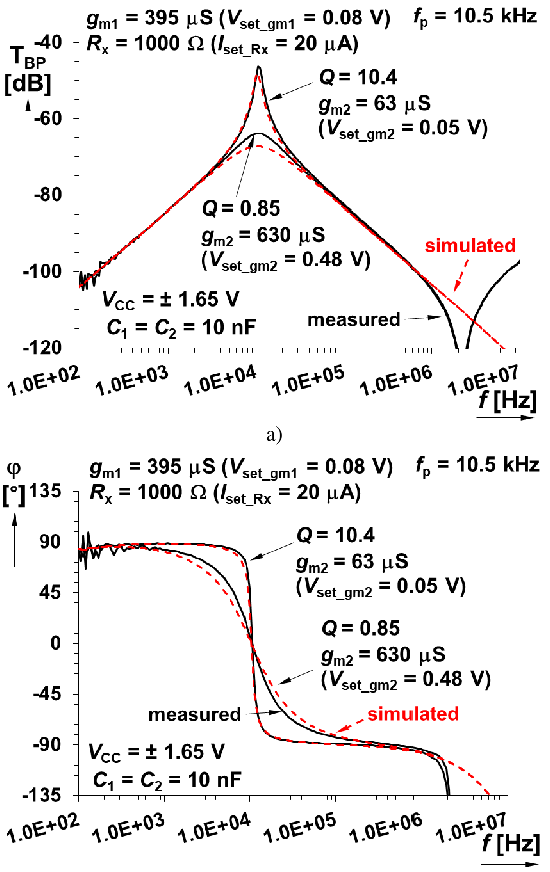
Fig. 2. Controllable biquadratic trans-admittance mode filter employing CC-VDCCDITA in configuration providing: a) LP response, b) BP response.

IV. EXPERIMENTAL RESULTS

Design parameters of the filters are as follows: $f_p = 10$ kHz, $Q_p = 1$ considering $C_1 = C_2 = C = 10$ nF, $R_X = 1$ kΩ ($I_{set\_Rx} \cong 20$ μA). Then, resulting parameters for initial setting of the filters are: $g_{m1} = 395$ μS ($V_{set\_gm1} = 0.08$ V) and $g_{m2} = 630$ μS ($V_{set\_gm2} = 0.48$ V). Note that dependency of g_{m2} (CMOS MLT) on control voltage (V_{set_gm2}) is not the same as in case of g_{m1} (BJT MLT) [11]. Figure 3 shows simulated and measured frequency responses of the filter in BP configuration. Decreasing of the value of g_{m2} (5) leads to increased value of Q_p as documented also in Fig. 3. Important parameters are shown directly in figures. Figure 4 brings results of the LP response for two different values of Q_p.

The adjustment of pass-band gain of BP response together with f_p tuning was also tested by R_X and g_{m1} variation. Variation of g_{m1} results in pole frequency and quality factor change as shown in Fig. 5 for $g_{m1} = 253$ μS and 2467 μS ($V_{set\_gm1} = 0.05$ V and 0.5 V). This adjustment allows theoretical change of pass-band gain from –68 up to –48 dB ($\Delta T_{0(max)} = 20$ dB) and pole frequency tuning from 7.8 kHz up to 24.6 kHz. Real experiments yield $T_{0(max)}$ change from –69 up to –49 dB and f_p between 8.4 kHz and 27 kHz.

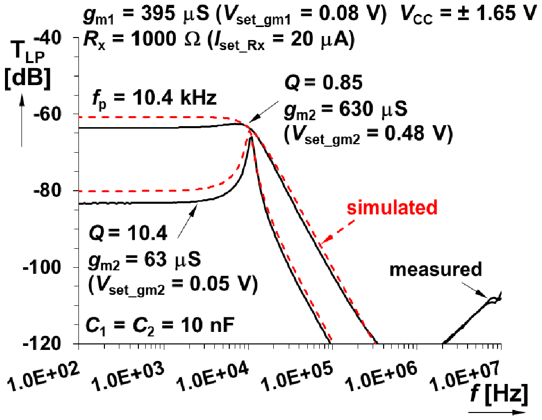
The adjustment of R_X (by I_{set_RX}) offers reduced range of tuning of center frequency f_p and $T_{0(max)}$ than in case of control by g_{m1} (V_{set_gm1}). The theoretically expected $T_{0(max)}$ tuning range is from –69 up to –59 dB ($\Delta T_{0(max)} = 10$ dB). Experimentally achieved value is $\Delta T_{0(max)} = 8$ dB, $T_{0(max)}$ can be varied from –72 dB up to –64 dB. The impact is significantly lower due to the character of R_X dependence on I_{set_RX}. The similar limitations are valid also for f_p (5.9 kHz → 14.1 kHz theoretically; 9.5 kHz → 16.9 kHz experimentally). Results are illustrated in Fig. 6. However, it can be useful when small-step of change of f_p and consequently also $T_{0(max)}$ is useful for application. The disadvantage of this approach (R_X) consists in the accuracy of R_X dependence on I_{set_RX} (there are significant fabrication tolerances that cannot be neglected).



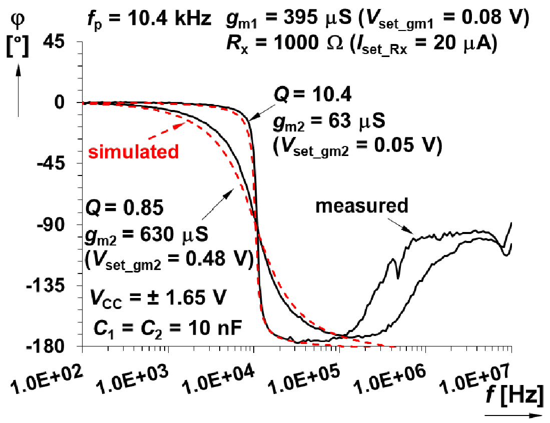
a)

b)

Fig. 3. Comparison of measured and simulated frequency responses of proposed trans-admittance filter in BP configuration: a) magnitude responses, b) phase responses.



a)



b)

Fig. 4. Comparison of measured and simulated frequency responses of proposed trans-admittance filter in LP configuration: a) magnitude responses, b) phase responses.

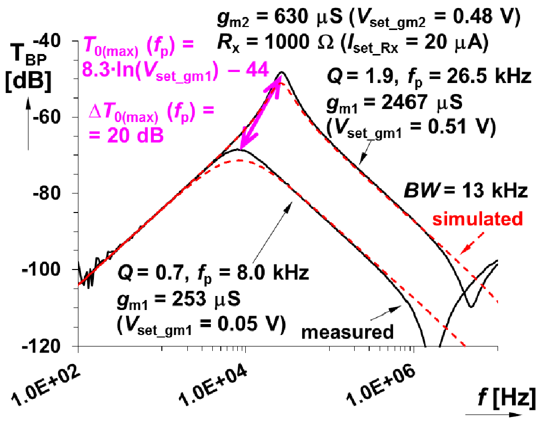


Fig. 5. Exemplary magnitude responses of the trans-admittance mode filter for: g_{m1} (V_{set_gm1}) variation (simulation vs. measurement).

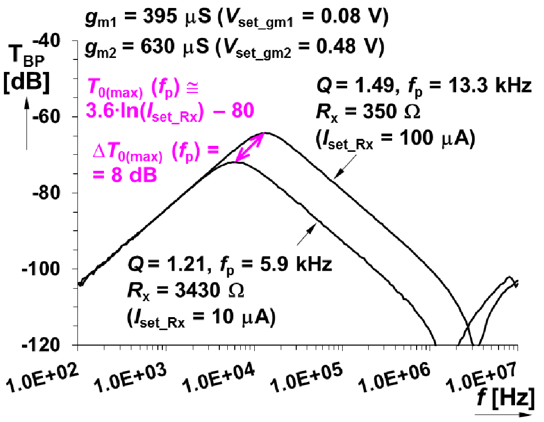


Fig. 6. Exemplary magnitude responses of the trans-admittance mode filter for: R_X (I_{set_RX}) variation.

V. Comparison of Proposed Filters with The State of the Art

Both proposed solutions of the trans-admittance filter (Fig. 2) has these advantages available simultaneously: a) all passive elements grounded, b) adjusting of quality factor independent on pole frequency, c) simple change between BP and LP response (reconnection of single terminal), d) high input impedance, e) relatively low (in dependence on R_X) output impedance. Table I brings comparison of relevant recently developed trans-admittance-mode filters. However, their complexity is not similar to proposed circuit in Fig. 2. These solutions target to full universality and, therefore, more than one active element is required in majority of them. Our solution offers lower multifunctionality (only LP and BP responses are available) but simple electronic controllability of quality factor is possible. It is not the case in many of recent and more complex solutions [14]-[21].

TABLE I. Comparison of Relevant Reported Selected Trans-Admittance-Mode Biquads.

Reference	Active elements	Number of active/passive elements	Grounded C	Transfer functions available	Electronic tunability of pole frequency	Electronic control of Q
[14]	CCII	3/5	No	HP, BP, LP	No	No
[15]	FTFN	3/5	No	HP, BP, LP	No	No
[16]	CDTA	2/4	Yes	HP, BP, LP, BR, AP	N/A	N/A
[17]	CDTA	2/4	Yes	HP, BP, LP, BR, AP	N/A	N/A
[18]	VDTA	2/2	Yes	HP, BP, LP, BR, AP	N/A	N/A
[19]	MO-CCCII	3/2	Yes	HP, BP, LP, BR, AP	Yes	N/A
[20]	MO-CCCII	3/2	Yes	HP, BP, LP, BR, AP	Yes	N/A
[21]	MOCDTA	2/4	Yes	HP, BP, LP, BR	N/A	N/A
proposed	CC-VDCCDITA	1/2	Yes	LP, BP	Yes	Yes

Notes:
CCII – current conveyor of second generation; CC-VDCCDITA – current controlled voltage differencing current conveyor differential input transconductance amplifier; CDTA – current differencing transconductance amplifier; FTFN – four terminal floating nullor; MO-CCCII – multi-output current controllable CCII; MO-CDTA – multi-output CDTA; OFCC – operating floating current conveyor; VDTA – voltage differencing transconductance amplifier; N/A – not available, not solved or not tested; HP – high-pass filter, BP – band-pass filter, LP – low-pass filter, BR – band-reject filter, AP – all-pass filter.

VI. Conclusion

Application example of active element presented in this contribution indicates useful features of modular approach and simplification of overall circuitry (all parts of CC-VDCCDITA are integrated on single chip package [11]). Proposed application was tested in bands from hundreds of Hz up to ten MHz because this operational band fits performance of developed modular device. Experiments confirmed adjustable features of presented filtering topology (quality factor and center frequency control). The effect of adjustability in case of BP response (arranged by R_X and g_{m2} parameters) suitable for adaptive applications brings two ways of pass-band gain and center frequency tuning simultaneously. The g_{m1} adjustment provides more than two-times wider change of f_p (8.4→27 kHz) and $T_{0(\max)}$ (–69 → –49 dB) than R_X driving. But both methods can be useful when different trend of influence on frequency response is necessary. The future design expects modification of topology allowing reconnection-less purposes [13] and more transfer functions (better multifunctionality) than presented examples.

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