ELECTRONICALLY ADJUSTABLE TRIPLE-INPUT SINGLE-OUTPUT FILTER WITH VOLTAGE DIFFERENCING TRANSCONDUCTANCE AMPLIFIER

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Key words: Current mode, Triple-input single-output (TISO) filter, Universal filter, Voltage differencing transconductance amplifiers (VDTA).

The main aim of this paper is to present a solution of the triple-input single-output (TISO) filter with mutually independent adjustable pole frequency and with quality factor. The filter is universal, electronically adjustable; it operates in the current mode and includes only two active elements – the so-called voltage differencing transconductance amplifiers (VDTA), – each of them with two controllable transconductances (g_m). The implementation of a VDTA element in the 0.18 μm CMOS technology is also included and this model is used in detailed simulation of the proposed active element and also of the proposed universal filter.

1. INTRODUCTION

A brief introduction to recently reported controllable active elements is given in [1]. Some active elements which have two or more externally controllable parameters have already been published. The control is usually performed by bias voltage or bias current. One typical example of active element with two-parameter control is a modification of the current differencing transconductance amplifier (CDTA) [2, 3], where R_x and g_m are controlled by DC bias currents [4, 5]. Several active elements, based on the operational transconductance amplifier (OTA) [1, 6] and the current conveyor of second generation (CCII) [7, 8], have been also proposed. For example, the current conveyor transconductance amplifier (CCTA) [9] utilizes independent R_x and g_m control [10]. The modification of CCTA presented in [11] employs current gain control, where a current conveyor with adjustable gain flowing from X to Z terminal is used. Among other things, the voltage differencing transconductance amplifier (VDTA) [12−16] is another active block recently introduced. This element was derived from the previously introduced CDTA element, in which the current differencing unit at the front-end

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Rev. Roum. Sci. Techn. – Électrotechn. et Énerg., **59**, *2*, p. 163–172, Bucarest, 2014

part is replaced by the voltage differencer. The VDTA is actually composed of two voltage-controlled current sources (represented by OTAs) with the required number of outputs and these sub-circuits are interconnected internally. VDTA solutions therefore provide electronic tuning ability through their two independent transconductance gains and therefore VDTA is very suitable for electronically tunable circuits.

Active elements with more than one controllable parameter are very useful in circuit synthesis. They usually provide electronic control of more than one parameter in the final filtering solution. In the case of a filter, it is usually the pole frequency and the quality factor. Only one or two active elements are sufficient in many cases in order to obtain a second-order solution.

We conducted a study of several hitherto multifunctional or universal filtering solutions with VDTA [12−16] and the results are summarized in Table 1.

We found the following drawbacks of the proposed applications:

– Not all parameters of the filter are adjustable independently and electronically [12, 14, 15].

– Not all passive elements are grounded or outputs are taken from passive elements and therefore additional buffering is required [12, 14, 15],

– Copies or inversions of input current are required [15, 16] (in the case of our filter, copies are necesary only for the band-stop and all-pass filtering functions).

Table 1

Detailed comparison of most of VDTA-based filters published to date

Reference	Number of VDTA active elements	Current mode (CM) or Voltage Mode (VM)	Type of filter – Single Input Triple Output (SITO), Triple Input Single Output (TISO) , Multiple Input Multiple Output (MIMO)	Number of simulated transfer functions (five standard functions are: LP, BP, HP, BS, AP)	All output(s) of filter taken from separate output(s) of active element – high impedance output (for CM), low impedance output (for VM)
[12]	1	CM	SITO	3	no
[13]	2	CM	SITO	3	yes
[14]	1	VM	MIMO	3	no
[15]	1	CM	SITO	5	no
[16]	2	CM	TISO	5	yes
Proposed	2	CM	TISO	5	yes

Table 1

Detailed comparison of the most of hitherto published VDTA based filters (continued)

Reference	Number and type of passive elements – capacitor (*C*), resistor (*R*)	Independent electronic control of ω_0	Independent electronic control of *Q*	CMOS technology [µm] / supply voltage [V]	Copies, inversions or multiples of input signal required for particular functions; remarks
[12]	2x *C*	yes	no	0.35 / ±2	no (BS, AP not available)
[13]	2x *C*	yes	yes	0.18 / ±0.6	no (BS, AP not available or not tested)
[14]	2x *C**	yes	no	0.18 / ±0.9	no (BS, AP not available or not tested)
[15]	2x *C*, 1x *R*	no	no	0.18 / ±1	yes, copies (for BS and AP)
[16]	2x *C*	yes	yes	0.35 / ±2	yes, copies, inversions and ½ (for HP, BS and AP)
Proposed	2x *C*, 2x *R*	yes	yes	0.18 / ±1	yes, copies (for BS and AP)

* one capacitor is floating (not grounded)

This paper is divided into two main parts. The first part deals with the explanation of VDTA behaviour, which is supported by simulations using the CMOS model of the proposed element. The second part discusses the application of the VDTA-based structure utilized as universal current-mode filter.

2. VOLTAGE DIFFERENCING TRANSCONDUCTANCE AMPLIFIER

The VDTA element is a simple active block that consists actually of two interconnected transconductance sections. Each of them provides two independent electronically adjustable transconductances (g_{m1} and g_{m2}). A number of outputs of the first and the second section varies according to the particular requirements of intended application ([12−16]). The basic structure of a particular variant of VDTA active element is shown in Fig. 1a, the schematic symbol in Fig. 1b.

VDTA has two voltage inputs (*p* and *n*), a small number of auxiliary high-impedance ports (*z*+ and z–, i.e. positive and negative output of first OTA section) and positive and negative current outputs (*x*+ and *x*–). The input of the second section (OTA2) is connected directly to the *z*+ output of the first section (OTA1).

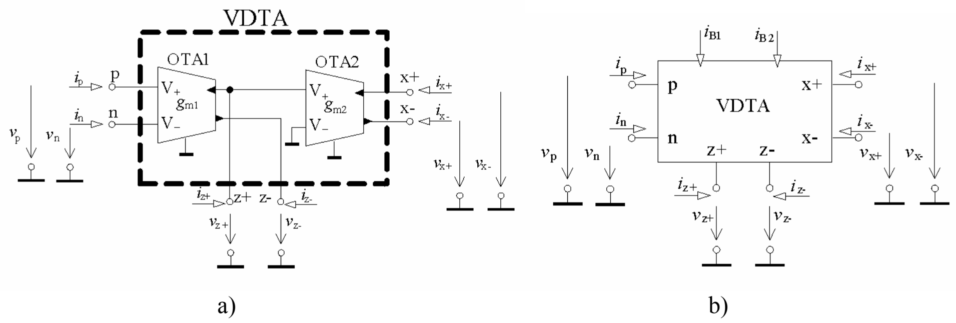


Fig. 1 – Voltage differencing transconductance amplifier (VDTA) with two independent electronically adjustable transconductances: a) basic structure; b) schematic symbol.

Outer behaviour of the VDTA element is described by the following matrix:

$$\begin{bmatrix} i_p \\ i_n \\ i_{z+} \\ i_{z-} \\ i_{x+} \\ i_{x-} \end{bmatrix} = \begin{bmatrix} 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ g_{m1} & -g_{m1} & 0 & 0 \\ -g_{m1} & g_{m1} & 0 & 0 \\ 0 & 0 & g_{m2} & 0 \\ 0 & 0 & -g_{m2} & 0 \end{bmatrix} \cdot \begin{bmatrix} v_p \\ v_n \\ v_{z+} \\ v_{z-} \end{bmatrix}. \qquad (1)$$

The basic structure from Fig. 1a was the starting point for the design of the CMOS implementation of VDTA shown in Fig. 2. The transistor solution of both OTA sections was derived from the structure presented in [16] and it was supplemented by the well-known structure of multiple-output current conveyor of the second generation (MO-CCII). Particular transistor dimensions are included in the Fig. 2.

The structure has three main parts: two OTA sections and one MO-CCII. MO-CCII serves as a two-output current follower that helps to obtain the required number of outputs of the first OTA section. The transconductance of the first section is controlled electronically by current I_{B1}, the second transconductance is also controlled electronically – by current I_{B2}. It is obvious that the number of outputs can easily be changed according to particular requirements (in the case of OTA1 stage). The proposed CMOS model was simulated and analyzed in the TSMC (Taiwan Semiconductor) LO (Logic Process) EPI (Epitaxial wafers) 0.18 μm technology [17] in PSpice. Some of the important simulation results of VDTA model are included in this paper. Figure 3 shows the DC performance of the first OTA section for three values of control current I_{B1}, and the AC performance of the first OTA section for the same three values of control current. Figure 4 includes the dependence of g_{m1} of OTA on control current I_{B1}.

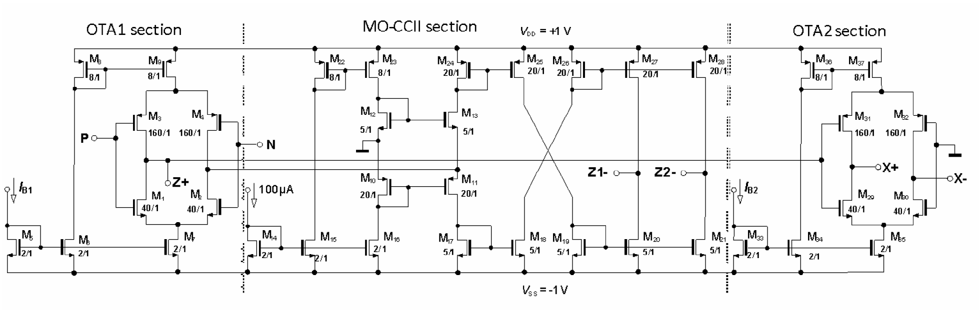
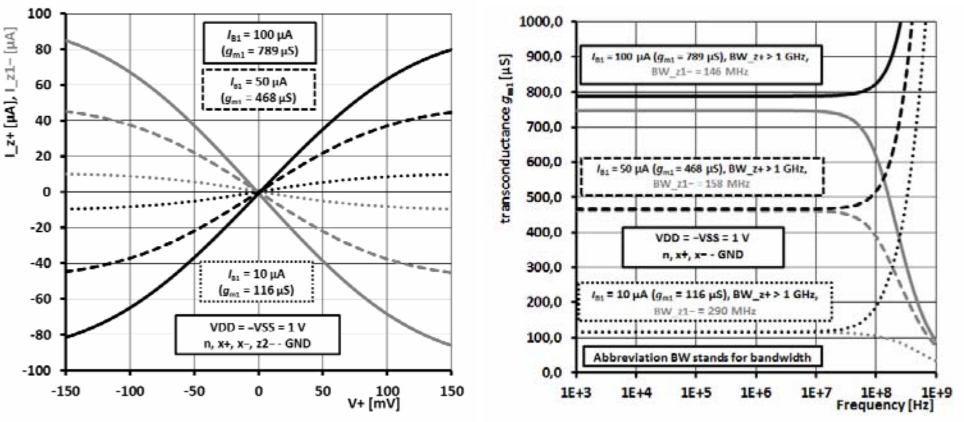


Fig. 2 – Designed CMOS implementation of proposed VDTA active element with transistor dimensions.



a) b)

Fig. 3 – OTA performance (first section of VDTA) for selected values of control current: a) DC; b) AC. Black lines represent response on the $z+$ output, grey lines are responses on $z-$ output. There are three different control currents (and therefore also three different g_{m1}), first is given by solid line, second by dashed line and third by dotted line.

Important DC and AC parameters of the VDTA element are summarized in Table 2. It is obvious that adjustment of g_m (I_{bias}) has significant impact on obtained parameters.

3. EXAMPLE OF FILTERING SOLUTION WITH VDTA

The proposed active element is very suitable for the design of electronically controllable filters. This section presents an example of the current-mode TISO universal controllable filter with only two VDTAs. Its structure, whose benefits were described in the introductory part of the paper, is shown in Fig. 5.

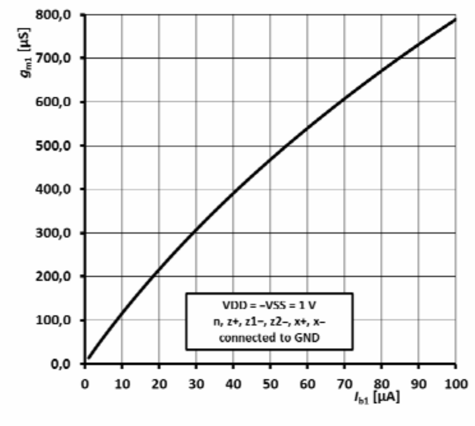


Fig. 4 – Dependence of g_{m1} of OTA (first section of VDTA) on control current.

Table 2

Important DC and AC parameters of VDTA element for two particular values of control current

Parameter	Value for $I_{b1} = I_{b2} = 10$ μA	Value for $I_{b1} = I_{b2} = 100$ μA
p and *n* input dc resistance, $R_p = R_n$	> 1 GΩ	> 1 GΩ
z+ output dc resistance, R_{z+}	1.33 MΩ	187 kΩ
*z*1− and *z*2− output dc resistance, $R_{z1-} = R_{z2-}$	149 kΩ	149 kΩ
x+ and *x*− output dc resistance, $R_{x+} = R_{x-}$	663 kΩ	93 kΩ
3dB attenuation for transfer from *p* input to *z*+ output, K_{-3dB} (p → z+)	> 1 GHz	> 1 GHz
3dB attenuation for transfer from *p* input to *z*− outputs, K_{-3dB} (p → z1−) = K_{-3dB} (p → z2−)	290 MHz	146 MHz
transconductance of first and second OTA, $g_{m1} = g_{m2}$	115 μS	789 μS

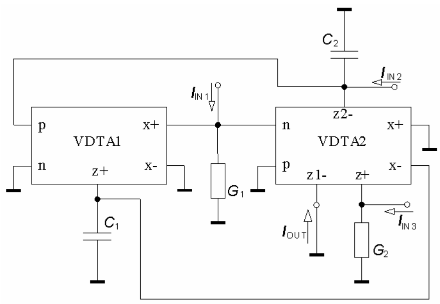


Fig. 5 – Structure of TISO universal controllable filter with two VDTAs.

The ideal transfer functions (low pass = LP, inverting band pass = iBP, high pass = HP, band stop = BS, all pass = AP) of this filter are as follows:

$$K_{LP}(\boldsymbol{s}) = \frac{\boldsymbol{I}_{OUT}}{\boldsymbol{I}_{IN2}} = \frac{G_2 g_{m1} g_{m2} g_{m3}}{D(\boldsymbol{s})} \ , \tag{2}$$

$$K_{iBP}(\boldsymbol{s}) = \frac{\boldsymbol{I}_{OUT}}{\boldsymbol{I}_{IN3}} = \frac{-\boldsymbol{s} C_2 g_{m2} g_{m3} g_{m4}}{D(\boldsymbol{s})} \ , \tag{3}$$

$$K_{HP}(\boldsymbol{s}) = \frac{\boldsymbol{I}_{OUT}}{\boldsymbol{I}_{IN1}} = \frac{\boldsymbol{s}^2 C_1 C_2 G_2 g_{m3}}{D(\boldsymbol{s})} \ , \tag{4}$$

$$K_{BS}(\boldsymbol{s}) = \frac{\boldsymbol{I}_{OUT}}{\boldsymbol{I}_{IN1} + \boldsymbol{I}_{IN2}} = \frac{\boldsymbol{s}^2 C_1 C_2 G_2 g_{m3} + G_2 g_{m1} g_{m2} g_{m3}}{D(\boldsymbol{s})} \ , \tag{5}$$

$$K_{AP}(\boldsymbol{s}) = \frac{\boldsymbol{I}_{OUT}}{\boldsymbol{I}_{IN1} + \boldsymbol{I}_{IN2} + \boldsymbol{I}_{IN3}} = \\ = \frac{\boldsymbol{s}^2 C_1 C_2 G_2 g_{m3} - \boldsymbol{s} C_2 g_{m2} g_{m3} g_{m4} + G_2 g_{m1} g_{m2} g_{m3}}{D(\boldsymbol{s})} \ , \tag{6}$$

$$D(\boldsymbol{s}) = \boldsymbol{s}^2 C_1 C_2 G_2 G_1 + \boldsymbol{s} C_2 g_{m2} g_{m3} g_{m4} + G_2 g_{m1} g_{m2} g_{m3} \ , \tag{7}$$

where g_{m1} and g_{m2} are the transconductances of VDTA1, and g_{m3} and g_{m4} are the transconductances of VDTA2. It is obvious that the filter is stable and these transfer functions are of the second order. It is also obvious that two copies of input current are required for the BS filter and three copies of input current are required for the AP filter. Input currents that are not mentioned in the foregoing transfer functions are considered as zero. If $G_1 = g_{m3}$, unity gain (0 dB) is obtained in the pass band of every transfer function. If this is ensured, the center (pole) frequency and quality factor are:

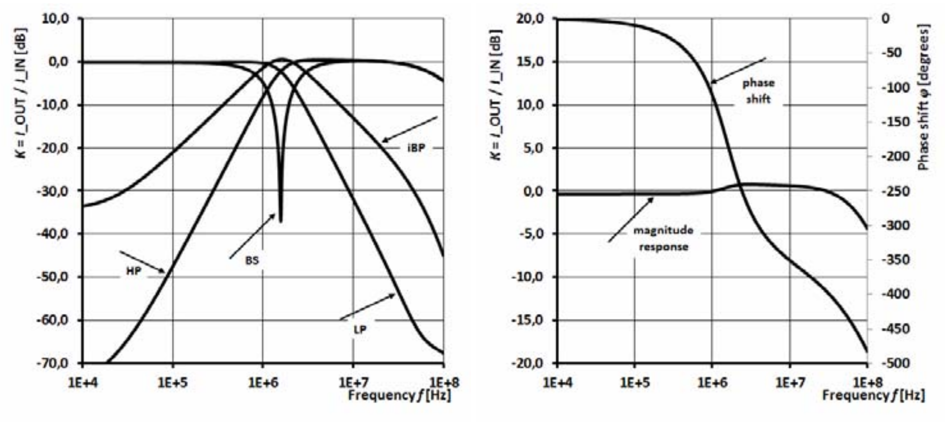
$$f_0 = \frac{1}{2\pi}\sqrt{\frac{g_{m1} g_{m2}}{C_1 C_2}} \ , \quad Q = \frac{G_2}{g_{m4}}\sqrt{\frac{g_{m1} C_1}{g_{m2} C_2}} \ . \tag{8}$$

The center frequency could be tuned independently of the quality factor by simultaneously changing g_{m1} and g_{m2}, while keeping $g_{m1} = g_{m2}$. The ratio of G_2 and g_{m4} could be used for independent adjustment of the quality factor (if G_2 is higher, Q is also higher, and if g_{m4} is lower, Q is higher). If only electronic control is required, only g_{m4} should be used for Q control.

The parameters of the filter and passive components are calculated as follows:

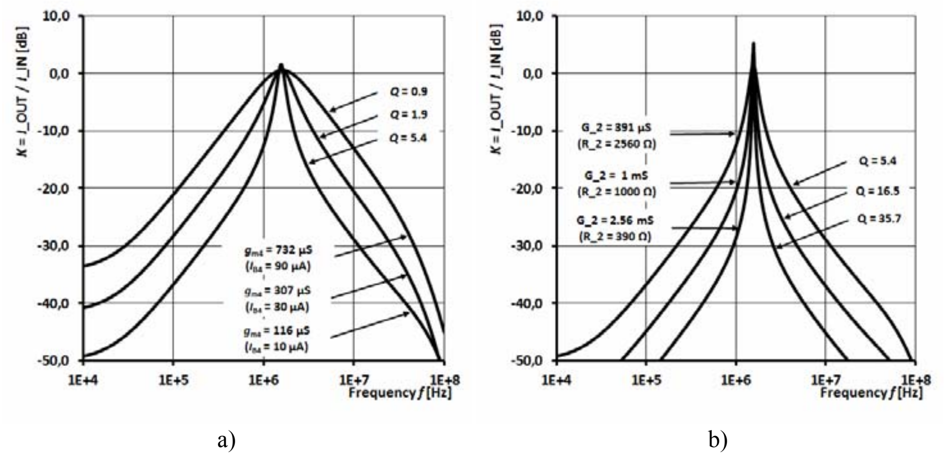
The starting pole frequency f_p = 1.6 MHz has been obtained for $g_{m1} = g_{m2}$ = 621 μS ($I_{b1} = I_{b2}$ = 72 μA), G_1 =769 μS (R_1 = 1.3 kΩ), g_{m3} = 769 μS (I_{b3} = 96.5 μA), C_1 = 82 pF, C_2 = 47 pF. The starting value of the quality factor is Q = 0.707 (Butterworth approximation) and it is obtained when G_2 = 391 μS (R_2 = 2.56 kΩ) and g_{m4} = 732 μS (I_{b4} = 90 μA).

The most significant simulation results are presented in Figs. 6–8.



a) b)

Fig. 6 – Magnitude (and phase) responses for starting parameters, f_p = 1.6 MHz and Q = 0.707: a) LP, iBP, HP and BS functions; b) AP function



a) b)

Fig. 7 – Quality factor electronic control (f_p = 1.6 MHz): magnitude response of iBP: a) for three different values of g_{m4}; b) additional possibility of control by value of G_2 (when g_{m4} = 10 μA).

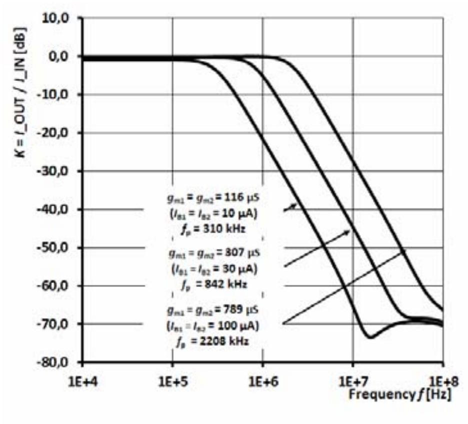


Fig. 8 – Pole frequency control with constant quality factor: Magnitude response of LP function for three different values of $g_{m1} = g_{m2}$.

4. **CONCLUSION**

The filtering solution presented above has many advantages due to the electronic control of four parameters: g_{m1}, g_{m2}, g_{m3} and g_{m4}. The filter consists of two active elements and four passive elements, but some of them could be omitted if the control of pole frequency independently of the quality factor and/or some of the filtering functions are not required in a particular application. The control possibilities were demonstrated only on the band pass and low pass responses, but tuning is also possible in the case of other filtering functions. The main advantages of the final universal filtering solution are: parameters of the filter can be adjusted electronically and independent of each other, not many active and passive elements are required, all passive elements are grounded and no output is taken from the passive element and therefore no additional buffering is required.

ACKNOWLEDGEMENTS

This research work was funded by Czech Science Foundation projects 14-24186P and 102/09/1681. The described research was performed in laboratories supported by the SIX project; registration No CZ.1.05/2.1.00/03.0072, operational programme Research and Development for Innovation.

Received on 21 Octomber, 2013

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