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 \( \mu \)m 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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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 necessary only for the band-stop and all-pass filtering functions).

Table 1
Detailed comparison of most of VDTA-based filters published to date

<table>
<thead>
<tr>
<th>Reference</th>
<th>Number of VDTA active elements</th>
<th>Current mode (CM) or Voltage Mode (VM)</th>
<th>Type of filter – Single Input Triple-Output (SITO), Triple Input Single-Output (TISO), Multiple Input Multiple Output (MIMO)</th>
<th>Number of simulated transfer functions (five standard functions: LP, BP, HP, BS, AP)</th>
<th>All output(s) of filter taken from separate output(s) of active element – high impedance output (for CM), low impedance output (for VM)</th>
</tr>
</thead>
<tbody>
<tr>
<td>[12]</td>
<td>1</td>
<td>CM</td>
<td>SITO</td>
<td>3</td>
<td>no</td>
</tr>
<tr>
<td>[13]</td>
<td>2</td>
<td>CM</td>
<td>SITO</td>
<td>3</td>
<td>yes</td>
</tr>
<tr>
<td>[14]</td>
<td>1</td>
<td>VM</td>
<td>MIMO</td>
<td>3</td>
<td>no</td>
</tr>
<tr>
<td>[15]</td>
<td>1</td>
<td>CM</td>
<td>SITO</td>
<td>5</td>
<td>no</td>
</tr>
<tr>
<td>[16]</td>
<td>2</td>
<td>CM</td>
<td>TISO</td>
<td>5</td>
<td>yes</td>
</tr>
<tr>
<td>Proposed</td>
<td>2</td>
<td>CM</td>
<td>TISO</td>
<td>5</td>
<td>yes</td>
</tr>
</tbody>
</table>
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).
Outer behaviour of the VDTA element is described by the following matrix:

\[
\begin{bmatrix}
i_p \\
i_n \\
i_{z+} \\
_i_{z-} \\
i_{x+} \\
i_{x-}
\end{bmatrix}
= \begin{bmatrix}
0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 \\
g_{m1} & -g_{m1} & 0 & 0 \\
-g_{m1} & g_{m1} & 0 & 0 \\
0 & 0 & g_{m2} & 0 \\
0 & 0 & -g_{m2} & 0
\end{bmatrix}
\begin{bmatrix}
v_p \\
v_n \\
v_{z+} \\
v_{z-} \\
v_{x+} \\
v_{x-}
\end{bmatrix}.
\]

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 \(I_{B1}\).
Filter with voltage differencing transconductance amplifier

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

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value for $I_{b1} = I_{b2} = 10 \mu A$</th>
<th>Value for $I_{b1} = I_{b2} = 100 \mu A$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$p$ and $n$ input dc resistance, $R_p = R_n$</td>
<td>&gt; 1 GΩ</td>
<td>&gt; 1 GΩ</td>
</tr>
<tr>
<td>$z^+$ output dc resistance, $R_{z+}$</td>
<td>1.33 MΩ</td>
<td>187 kΩ</td>
</tr>
<tr>
<td>$z^-$ and $z^-2$ output dc resistance, $R_{z1-} = R_{z2-}$</td>
<td>149 kΩ</td>
<td>149 kΩ</td>
</tr>
<tr>
<td>$x^+$ and $x^-$ output dc resistance, $R_{x+} = R_{x-}$</td>
<td>663 kΩ</td>
<td>93 kΩ</td>
</tr>
<tr>
<td>3dB attenuation for transfer from $p$ input to $z^+$ output, $K_{-3dB (p \rightarrow z^+)}$</td>
<td>&gt; 1 GHz</td>
<td>&gt; 1 GHz</td>
</tr>
<tr>
<td>3dB attenuation for transfer from $p$ input to $z^-$ outputs, $K_{-3dB (p \rightarrow z1-)} = K_{-3dB (p \rightarrow z2-)}$</td>
<td>290 MHz</td>
<td>146 MHz</td>
</tr>
<tr>
<td>transconductance of first and second OTA, $g_{m1} = g_{m2}$</td>
<td>115 µS</td>
<td>789 µS</td>
</tr>
</tbody>
</table>

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:
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:

$$f_0 = \frac{1}{2\pi} \sqrt{\frac{g_{m1}g_{m2}}{C_1C_2}}, \quad Q = \frac{G_2}{g_{m4}} \sqrt{\frac{g_{m1}C_1}{g_{m2}C_2}}.$$  

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 $g_{m1} = g_{m2} = 621 \ \mu S$ ($I_{b1} = I_{b2} = 72 \ \mu A$), $G_1 = 769 \ \mu S$ ($R_1 = 1.3 \ k\Omega$), $g_{m3} = 769 \ \mu S$ ($I_{b3} = 96.5 \ \mu A$), $C_1 = 82 \ \text{pF}$, $C_2 = 47 \ \text{pF}$. The starting value of the quality factor is $Q = 0.707$ (Butterworth approximation) and it is obtained when $G_2 = 391 \ \mu S$ ($R_2 = 2.56 \ k\Omega$) and $g_{m4} = 732 \ \mu S$ ($I_{b4} = 90 \ \mu A$).

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

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.

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 $g_{m4} = 10 \ \mu A$).
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.

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