Optimization of Elliptic Leap-Frog CDBA-Based Filters

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Abstract – A technique of passive elliptic ladder RLC filter simulation by active circuits with CDBA (Current-Differencing Buffered Amplifier) elements is described in the paper. Methods of filter transfiguration towards a circuit employing only grounded impedances are shown. Rules for carrying out dynamic range optimization and changing the impedance levels can then be applied to this circuit.

Key-Words: - CDBA, ladder filter, Leap-Frog, SFG simulation.

1 Introduction

The CDBA (Current-Differencing Buffered Amplifier) circuit element introduced in [1] makes passive ladder filter simulation easy [2]. A technique for elliptic lowpass filter synthesis, which is obviously applicable to arbitrary ladder structures, is described in [3]. Its specific disadvantage consists in the relatively high number of working capacitors that are necessary for the generation of transmission zeros.

In this paper we show a synthesis procedure for a filter with CDBA elements. The total number of capacitors of this filter is equal to the total number of inductors and capacitors in the original ladder filter. The resulting filter is an original passive ladder filter extended by an active subcircuit, which simulates floating inductors. Each floating inductor is synthetized by one grounded capacitor and the CDBA elements.

The final active filter thoroughly copies the ladder filter structure and therefore shares its excellent sensitivity properties. Its specific disadvantages are floating capacitors that participate in transmission zeros implementation. These capacitors make a consistent optimization of the active filter difficult, especially the upper bound of its dynamic range. Fortunately it is possible to transfer each floating capacitor to four grounded capacitors, and after the optimization to go back to the original, now modified structure.

This paper is organized as follows: In Section 2, basic information about the CDBA element is summarized, and a technique of floating inductor simulation by means of these elements is shown. In Section 3, reciprocal transfiguration methodology of two typical circuit structures with CDBA elements is explained. This methodology leads to equivalent circuits. Section 4 shows a concrete example of the synthesis of an elliptic lowpass filter with a minimum number of capacitors, and its transfiguration to a circuit employing grounded impedances only. In Section 5 two propositions are defined, helping to optimize the active filter with grounded impedances. In the final section, filter optimization and its transformation to a filter with floating capacitors are shown.

2 CDBA elements and floating inductor simulation

The behavioral model of an ideal CDBA and its schematic symbol are shown in Fig. 1. This element has two difference current inputs *p* and *n*. The difference of these currents flows from terminal *z* into an outside load. The voltage across the *z* terminal is transferred to the *w* terminal by a unity-gain buffer.

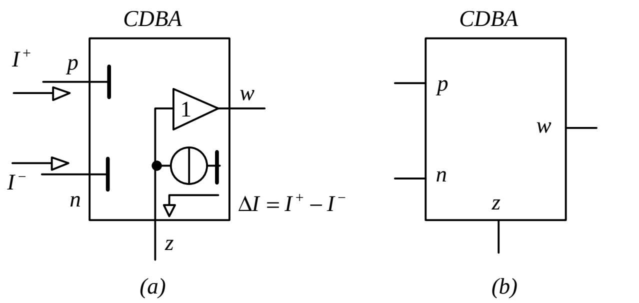

Fig. 1: (a) Behavioral model of CDBA element, (b) its schematic symbol.

The following simple equation results from the floating inductor scheme in Fig. 2 (a):

$$I_L = \frac{V_1 - V_2}{sL}.$$

Utilizing an auxiliary resistance $r > 0$, it can be transferred into the form

$$rI_L = \frac{V_1 / r - V_2 / r}{sL / r^2}. \quad (1)$$

The left-side quantity in Eq. 1 is a voltage, generated by CDBA on the *z* and *w* terminals, if terminals *p* and *n* are driven by currents V_1/r and V_2/r, respectively, and if a grounded capacitor of capacitance L/r^2 is connected to the *z* terminal. The middle CDBA element in Fig. 2 (b) is considered. Its output voltage is converted back into the currents by means of auxiliary resistors that are appropriately distributed to nodes 1 and 2 by outer CDBA elements.
In the case that further inductors in the original ladder filter are connected to the above inductor, it is possible to employ the outer CDBA elements in their simulation.

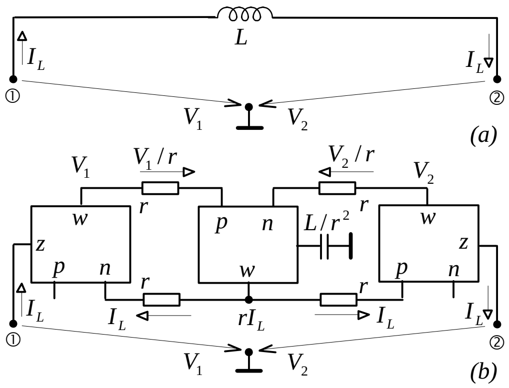

Fig. 2: (a) Floating inductor, (b) its alternative circuit with CDBAs.

3 Transfiguration of CDBA-based circuit structures

Consider the circuits in Fig. 3. We can talk about grounded impedances in both cases because *n*-terminal impedance is equal to zero. Regarding the same voltages on the *z* and *w* terminals, one can see that there are the same voltages on impedances Z_1 and Z_2 in Fig. (a). An analysis of both circuits would show that the circuits are equivalent. Passing from circuit (a) to circuit (b) leads to a simpler structure, in the case of identical character of impedances Z_1 and Z_2.
The connection of two CDBA elements with a floating impedance *Z* between their *z* terminals is shown in Fig. 4 (a). The circuits in Figs. (a), (b) and (c) are equivalent as results from simple calculations. In variants (b) and (c), all circuit impedances are connected in such a way that one of their terminations is at ground potential. We refer to these variants as circuits with grounded impedances.

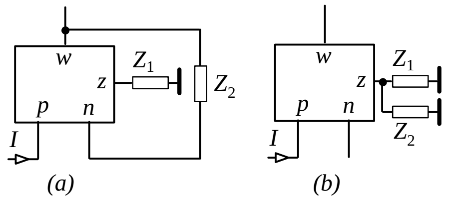

Fig. 3: Equivalent circuits with CDBAs.

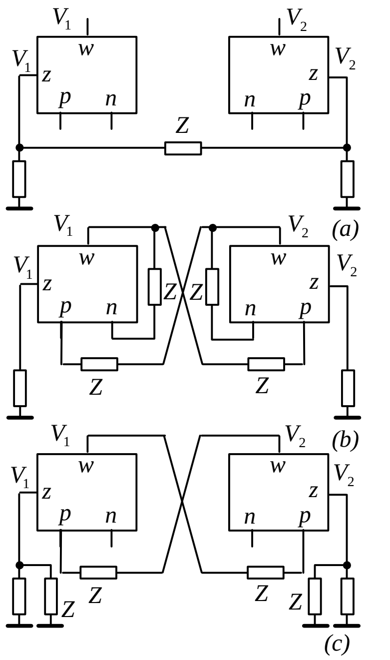

Fig. 4: Equivalent circuits with CDBAs.

4 Example of elliptic ladder filter simulation

Consider the ladder filter in Fig. 5. This current-mode fifth-order Cauer lowpass filter, designed by the NAF program [4], has 1MHz cut-off frequency, 3dB passband ripple and 60dB stopband attenuation from 1.5MHz stopband frequency.
The component values are as follows:

R=1kΩ, C_1=516pF, C_2=596pF, C_3=456pF, C_4=44.2pF, C_5=120pF, L_1=108μH, L_2=88.6μH.

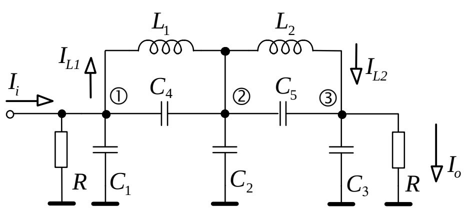

Fig. 5: Fifth-order elliptic RLC ladder lowpass filter.

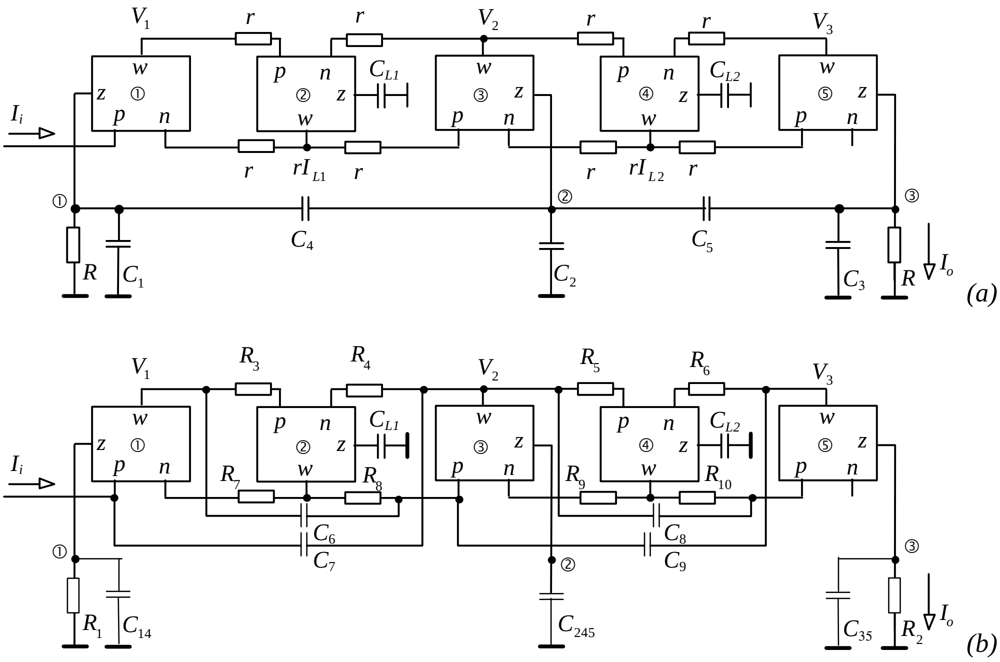

Fig. 6: Two variants of active filter, resulting from ladder filter in Fig. 5.

	(a)	*(b)*	*(c)*	*(d)*
R_1	1000	**1514**	1514	1514
R_2	1000	**2000**	**1000**	1000
R_3	1000	**1514**	1514	1514
R_4	1000	**1188**	1188	1188
R_5	1000	**1188**	1188	1188
R_6	1000	**2000**	2000	2000
R_7	1000	**457**	457	457
R_8	1000	**457**	457	457
R_9	1000	**437**	437	437
R_{10}	1000	**437**	**219**	219
C_{14}	560	**370**	370	**341**
C_{245}	760	**640**	640	**551**
C_{35}	576	**288**	**576**	**516**
C_{L1}	108	**236**	236	236
C_{L2}	89	**203**	203	203
C_4	-	**-**	-	**29**
C_5	-	**-**	-	**60**
C_6	44	**29**	29	**-**
C_7	44	**37**	37	**8®0**
C_8	120	**101**	**202**	**142**
C_9	120	**60**	60	**-**

Table 1: Component values of the filter in Fig. 6 (b), (a) initial, (b) after the optimization of the upper bound of dynamic range, (c) after setting the current passband gain to 1, (d) after backward transfiguration to the variant in Fig. 6 (a). All the resistances and capacitances are given in ohms and picofarads, respectively.

The active filter scheme in Fig. 6 (a) can be created using the simulation principle of floating inductor in Fig. 2 (b). The input current I_i can be advantageously applied to the low-impedance input *p* of the first CDBA.

Setting the auxiliary resistance to r = 1kΩ in the first design stage, we get the capacitances C_{L1}=108pF and C_{L2} = 88.6pF.

The following optimization will, among others, start from the real properties of the CDBAs employed. It is necessary to choose the impedance levels with respect to the maximum acceptable currents and parasitic capacitances.

The CDBA-based leapfrog structure in Fig. 6 (a) does not yield many degrees of freedom that could be used for filter optimization, especially to optimize the dynamic range and spread of component values. By means of filter transfiguration to the variant with grounded impedances (see Fig. 6 (b)), the required degrees of freedom can be obtained. The transfiguration is done according to the rule in Fig. 4. A parallel combination of appropriate capacitors in Fig. 6 (b) is denoted by subscript duplication, for example $C_{14} = C_1 + C_4$. Component values before optimization are summarized in Table 1, column (a).

5 Propositions facilitating optimization of CDBA-based Leapfrog structures with grounded impedances

The following propositions can be derived from the schematic in Fig. 6 (b). Similar propositions have been conceived earlier [5] for switched-capacitor filters and for continuous-time filters containing grounded *OpAmps* [6].

Proposition 1:

The transfer function from the input to voltage output w of a given CDBA will be increased a-times without affecting the transfer functions from the input into the outputs of the other CDBAs as follows:
We increase *a*-times the impedances of all components that are connected to the *w* and *z* terminals of a given CDBA.

This proposition can be utilized to set the required gain level and to optimize the dynamic range of the filter.

Proposition 2:

The impedance level "around" a given CDBA will be increased a-times without affecting arbitrary node voltage as follows:
We increase *a*-times the impedances of all components that are connected to the *z*, *p*, and *n* terminals of a given CDBA.

This proposition can be used to set the optimum impedance levels and to optimize the spread of *R* and *C* values.

6 Optimization example

The optimization procedure will be explained on the preliminarily designed filter in Fig. 6 (b). The CDBAs will be considered within the model published in [7]. This SPICE model of bipolar structure has been designed for the GBW of hundreds of MHz. The outlet currents can be up to 30mA (terminals *p*, *n*, and *z*) or up to 50mA (terminal *w*).
A checking computer simulation of CDBA output voltages of the filter in Fig. 6 (b) leads to the curves in Fig. 7.
Curve No. 5 confirms the required bandpass response. However, it is necessary to optimize the upper bound of dynamic range. The acquired transfer maxima are listed in Table 2. The "mult. factor *a*" in the third column gives how many times this gain must be increased to equalize all the maxima to the level of 0dB.

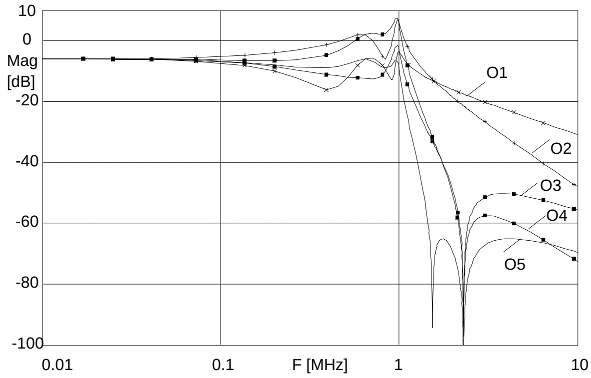

Fig. 7. Simulated frequency responses of voltages across the *w* – terminals of CDBAs Nos. 1 to 5 in Fig. 6 (b) for 1mA magnitude of the input current.

To equalize the transfer maxima, let us use Proposition 1. For example, modifying the transfer of CDBA No 1 will require multiplying resistances R_1 and R_3 and dividing capacitances C_{14} and C_6 by 1.514. The modified values of all resistances and capacitances are listed in Table 1, column (b). The checking computer simulation has confirmed the required equalization of the maxima.

w output of CDBA No.	max [dB]	mult. factor *a*
1	-3.600	1.514
2	+6.795	1/2.187
3	-1.497	1.188
4	+7.193	1/2.289
5	-6.022	2.000

Table 2: Transfer maxima across the outputs of individual CDBAs in Fig. 7.

However, the current transfer I_o/I_i is still 1/2. To set the value to 1 without affecting the valid voltage levels, we use Proposition 2: resistances R_2 and R_{10} will be decreased two times and simultaneously we double capacitances C_{35} and C_8. The final component values are summarized in column (c) in Table 1.
After the optimization, it is possible to go back to the structure with floating capacitors in Fig. 6 (a). It corresponds to a performed transformation from circuit (c) to circuit (a) as seen in Fig. 4. For this purpose, it is necessary to find the minimal capacitance from among C_6, C_7, C_{14} and C_{245}, which is $C_6 = 29$pF, and to transform it to floating capacitance $C_4 = 29$pF. It is necessary to decrease by this value each capacitance in this quaternion, which leads to the cancellation of C_6. The same procedure is then applied to the quaternion of capacitances C_8, C_9, C_{245} and C_{35}, with the results shown in Table 1, column (d). The resulting

capacitance C_7 is only 8pF. Computer simulation has shown that omitting this capacitance has no influence on frequency responses. The final active filter contains eight capacitors, which is only one more than in the original passive ladder filter.

The Monte Carlo analysis has been performed with capacitance and inductance tolerances of 5%. The analysis shows that the active and passive ladder filters have the same sensitivity properties on condition that auxiliary resistances, ensuring the function of CDBA elements, have tolerances not exceeding half the value of capacitance and inductance tolerances.

7 Conclusions

The methodology of the CDBA-based active Leap-Frog filter synthesis using passive RLC ladder filter simulation has been described in the paper. The dynamic-range and the impedance level optimizations are performed after transforming the filter to a structure with grounded impedances. A careful design can lead to very good sensitivity properties.

Acknowledgments

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