CTTA Current-Mode Filters Based on Current Dividers

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Abstract

Novel structure of active filter containing CTTA or CDTA building blocks is described. This current-mode structure can model arbitrary transfer function on the principle of simulation of high-order immittances. A simple design procedure flowing directly from the coefficients of transfer function is described.

1 Introduction

Non-cascade filters are known from the theory which model arbitrary transfer function on the principle of current divider and simulation of high-order immittances [1,2]. This smart "modular" filter structure is accompanied by its well-known drawbacks, namely higher sensitivities and complicated design procedures.

The problem of sensitivity properties appears particularly for high sensitivities of zeros and poles to coefficient values of transfer function. In general, these sensitivities increase with the order of transfer function and with the quality factors of zeros and poles. That is why this type of synthesis is unadvisable for filters with relatively high orders and for such approximations of frequency responses, leading to comparatively high quality factors of 2nd-order subsections. In other cases, whose typical representative can be e.g. 5th-order filter according to Bessel, Butterworth, or inverse Chebyshev approximation, with quality factors up to 10, the synthesis from the transfer function can bring interesting results. Then it is suitable to look for such circuit solutions which enable to eliminate the second often mentioned drawback, i.e. complicated design procedure.

The below circuit structure uses CTTA (Current Through Transconductance Amplifier) or CDTA (Current Difference Transconductance Amplifier) active elements [3]. The filter consists of a general admittance Y_0 and of the cascading blocks, each of which includes CTTA element and additional impedance. Given block then simulates an admittance which is directly proportional to the admittance of precedent block, to the additional impedance in the given block, and to the transconductance of given CTTA element. This structure leads to simple design procedures which will be demonstrated on a concrete example of 5th-order 50MHz lowpass filter.

2 CTTA and CDTA elements

The principle of CTTA and CDTA elements is described in [3]. The summary is given in Fig. 1. These elements consist of through-input (CCTA) or difference-input (CDTA) current amplifier and of the cascading multi-output OTA (Operational Transconductance Amplifier). In Fig. 1, always the difference outputs are given. The OTA input is led out to an auxiliary *z*-terminal.

The gain b of current amplifier and the transconductance g_m of OTA are either fixed or electronically adjustable to control filter parameters.

When one of the inputs is grounded, the CDTA and CTTA are interchangeable in given application. This is also a case of circuit structure described below.

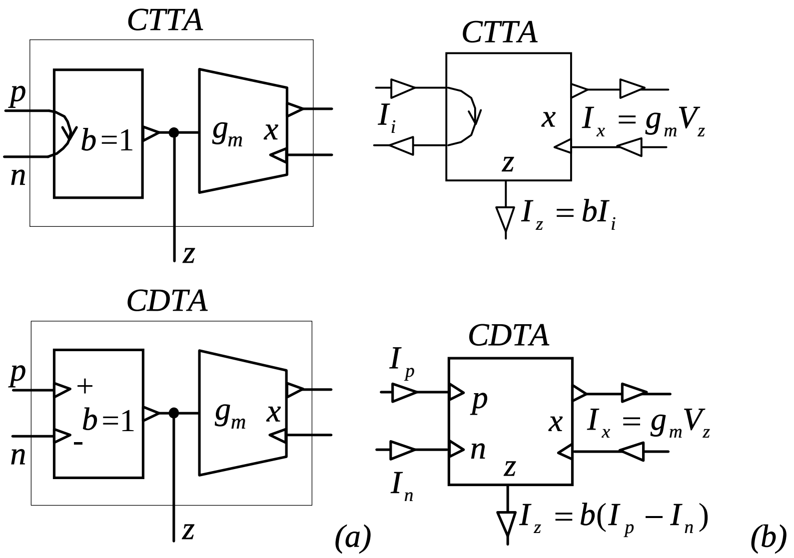

Fig. 1: (a) principal models of CTTA and CDTA elements, (b) their schematic symbols with designated terminal currents.

3 Generalized current dividers with CTTA elements

Let us consider circuit in Fig. 2 (a) containing *n* CTTA elements.

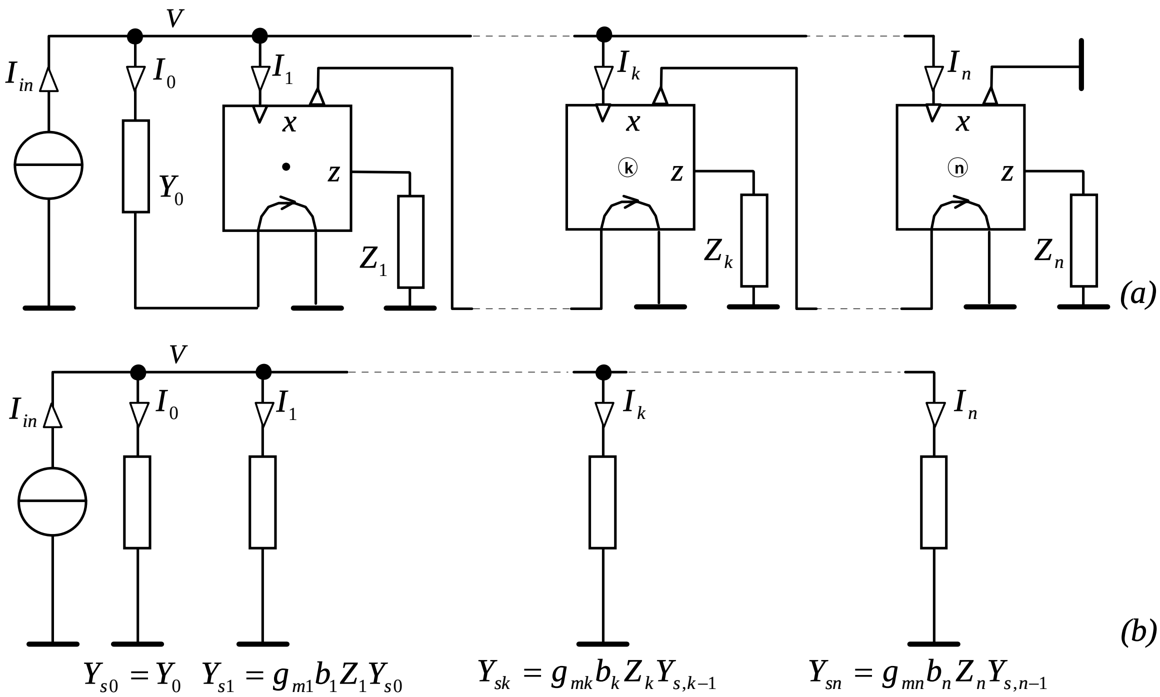

Fig. 2: (a) generalized current divider with CTTA elements, (b) its equivalent model.

The admittance Y_0 is connected to ground potential by one outlet through the input gate of CTTA No 1. That is why it behaves at input gate, to which the input source is connected, as a simulated admittance $Y_{s0} = Y_0$ (see Fig. 2b).
Current I_1 is given by the product of transconductance g_{m1} of CTTA No 1 and voltage on impedance Z_1, which is equal to current I_0 multiplied by current gain b_1 of CTTA No 1 and by impedance Z_1. The following is true:

$$I_1 = g_{m1} b_1 Z_1 I_0 = g_{m1} b_1 Z_1 Y_0 V \ .$$

The CTTA No 1 loads the input gate in such a way as simulated admittance $Y_{s1} = g_{m1} b_1 Z_1 Y_0$. Similarly, the CTTA No k loads the input gate and simulates the admittance

$$Y_{sk} = g_{mk} b_k Z_k Y_{s,k-1}, \; Y_{s0} = Y_0, \; k = 1, 2, \dots n. \tag{1}$$

The recurrent formula (1) has the following solution:

$$Y_{sk} = Y_0 \prod_{i=1}^{k} g_{mi} b_i Z_i, \; k = 0, 1, \dots n. \tag{2}$$

All the simulated admittances of current divider in Fig. 2 (b) are proportional to admittance Y_0. That is why dividing ratios will not depend on this admittance:

$$\frac{I_k}{I_{in}} = \frac{Y_{sk}}{\sum_{l=0}^{n} Y_{sl}} = \frac{\prod_{i=1}^{k} g_{mi} b_i Z_i}{\sum_{l=0}^{n} \prod_{i=1}^{l} g_{mi} b_i Z_i}, \; k = 0, 1, .., n. \tag{3}$$

Consider that all impedances Z_k, $k = 1, 2, .. n$, will be implemented by capacitors, i.e.

$$Z_k = \frac{1}{sC_k}, \; k = 1, 2, \dots n. \tag{4}$$

Substituting (4) into (3) and short arrangement yield the current transfers as follows:

$$\frac{I_k}{I_{in}} = \frac{c_{n-k} s^{n-k}}{\sum_{i=0}^{n} d_i s^i}, \; k = 0, 1, .., n, \tag{5}$$

where

$$c_k = d_k = \prod_{i=1}^{n-k} \frac{g_{mi} b_i}{C_i}, \; k = 0, 1, .., n. \tag{6}$$

By weighted summing the transfer functions (5), arbitrary nth-order transfer function can be implemented. This summing can be accomplished by linear combination of currents flowing through the input gates of individual CTTA elements.

4 Filter design from coefficients of transfer function

Let us consider nth-order transfer function

$$K(s) = \frac{\sum_{i=0}^{n} A_i s^i}{\sum_{i=0}^{n} B_i s^i}, \; B_n = 1, \tag{7}$$

which is given as input data for filter synthesis.
Comparing equations (5), (6), and (7) and considering other design requirements, the following procedure follows:

(a) Design of parameters of CTTA elements

Current gains b_k and transconductances g_{mk} will be set to equal values for all CTTA elements. The recommended values are as follows:

$$b = 1, \; g_m \approx B_{n-1} C, \tag{8}$$

where C is estimated dimension of working capacitances in the filter.

(b) Design of working capacitances

Capacitances C_1 to C_n which represent impedances Z_1 to Z_n in Fig. 2 (a) will be designed according to the following equations:

$$
\begin{aligned}
C_1 &= g_{m1} b_1 \frac{B_n}{B_{n-1}} = g_m \frac{1}{B_{n-1}} \\
C_2 &= g_{m2} b_2 \frac{B_{n-1}}{B_{n-2}} = g_m \frac{B_{n-1}}{B_{n-2}} \\
&\dots \\
C_k &= g_{mk} b_k \frac{B_{n-k+1}}{B_{n-k}} = g_m \frac{B_{n-k+1}}{B_{n-k}} \\
&\dots \\
C_n &= g_{mn} b_n \frac{B_1}{B_0} = g_m \frac{B_1}{B_0}
\end{aligned}
\tag{9}
$$

(c) Implementation of the numerator of transfer function (7)

Current I_k, $k = 0, 1, .., n$, flowing from the input gate of CTTA No k into ground, will be led into low-impedance input of current amplifier with the gain of

$$K_{ik} = \frac{A_{n-k}}{c_k}, \; k = 0, 1, .., n. \tag{10}$$

The amplifier will be certainly omitted when the corresponding gain is zero, or it will be replaced by short connection in case of the unity gain.

The outputs of the appropriate current amplifiers are then put to a summing node from which the output current flows into ground.

(d) Design of the admittance Y_0

Even if the current transfers are independent on the admittance Y_0, both the value and the character of this impedance affect input and voltage levels and other real properties of active filter. Furthermore, a DC offset current flowing through this admittance can cause serious stability problems, because this current is copied directly into the capacitor C_1. Considering these and other reasons, it is suitable to implement the admittance Y_0 by capacitor. The capacitance value should be chosen with respect to required impedance levels and the corresponding voltage level at the input gate, as well as to the terminal currents of CTTAs.

(e) Filter optimization

In case of non-optimal values of parameters g_{mk}, C_k , $k = 1, 2, .., n$ from the tentative design, it is possible to modify them to keep the ratios

$$\frac{g_{mk} b_k}{C_k}.$$

These variations can but also need not change the voltage levels at *z*-terminals of CTTAs which can also be optimized in this way. For example, increasing capacitance C_k from a problematic value of 5pF into 20pF must be accompanied by increasing b_k four times, or by increasing g_{mk} four times, or perhaps by doubling both the parameters. In the first case, the impedance level of the *z*-terminal is decreased, but we increased current into this terminal accordingly, such that the *z*-terminal voltage remains unchanged as well as current through the *x*-terminals which is derived from this voltage through the transconductance. In the second case, the voltage level at the *z*-terminal decreases four times, but the *x*-terminal current remains constant due to the increased transconductance. In the third case, voltage at the z-terminal decreases two times while I_x will be unchanged.

It is useful to optimize filter together with its computer simulation.

5 Design demonstration

The design objective is a lowpass filter according to inverse Chebyshev approximation, 50MHz cutoff frequency, 2dB passband ripple, and 40dB guarantied attenuation above 100MHz. The NAF program [1] generates results of the approximation task which are summarized in Table 1.

i	A_i	B_i
0	6.67889E42	6.67889E42
1	0	5.17857E34
2	2.97433E25	2.30507E26
3	0	6.47909E17
4	2.64914E7	1.13865E9
5	0	1

Table 1: Coefficients of transfer function (7) of filter designed by NAF program.

The procedure described in Chapter 4 leads to the filter structure in Fig. 3. This 5th-order filter is implemented by 5 CTTA elements, 6 capacitors, and 2 current amplifiers, or-let us say-attenuators.

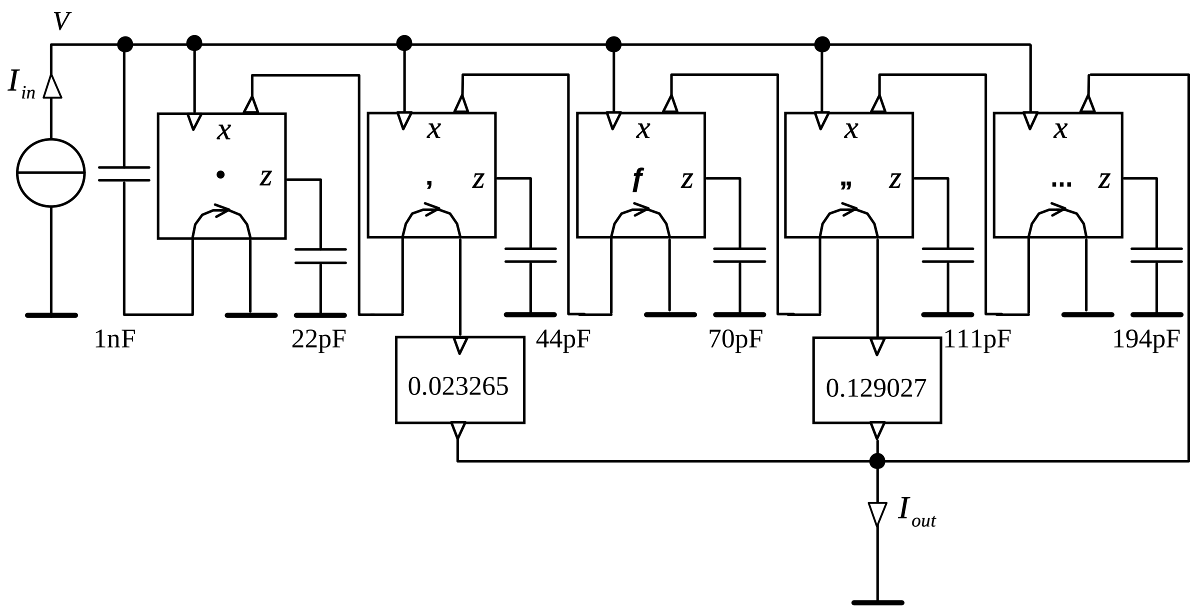

Fig. 3: Designed 50MHz lowpass filter. Parameters of all CTTAs are: g_m = 25mS, b =1.

The filter simulation has been performed by the SNAP [4] and SPICE programs. The corresponding models are described in [5,6].

Some results of SPICE simulation are shown in Fig. 4. The upper picture shows relatively good agreement between the frequency response and its ideal curve. It can be scanned from the bottom picture that for the input current of 1mA, the voltage at the input gate/*z*-terminals will not exceed value of 4.5mV/222mV. In other words, both the input source and the „*x*“-outputs of CTTAs work into the low-impedance load.

Since the transconductances of all CTTAs have the same value of 25mS, curves V(C1) to V(C5) represent also frequency dependent output currents „I_x“ of the individual CTTAs with the condition that the corresponding voltages are multiplied by 25mS. For the input current of 1mA, the output current maxima are from 1.5mA (CTTA No 5) to 5.6mA (CTTA No 2). In principle, the upper bound of the current dynamic range cannot be optimized in this filter structure. However, we can optimize the upper bound of *z*-terminal voltages by variation the g_m and b parameters according to Chapter 4(e).

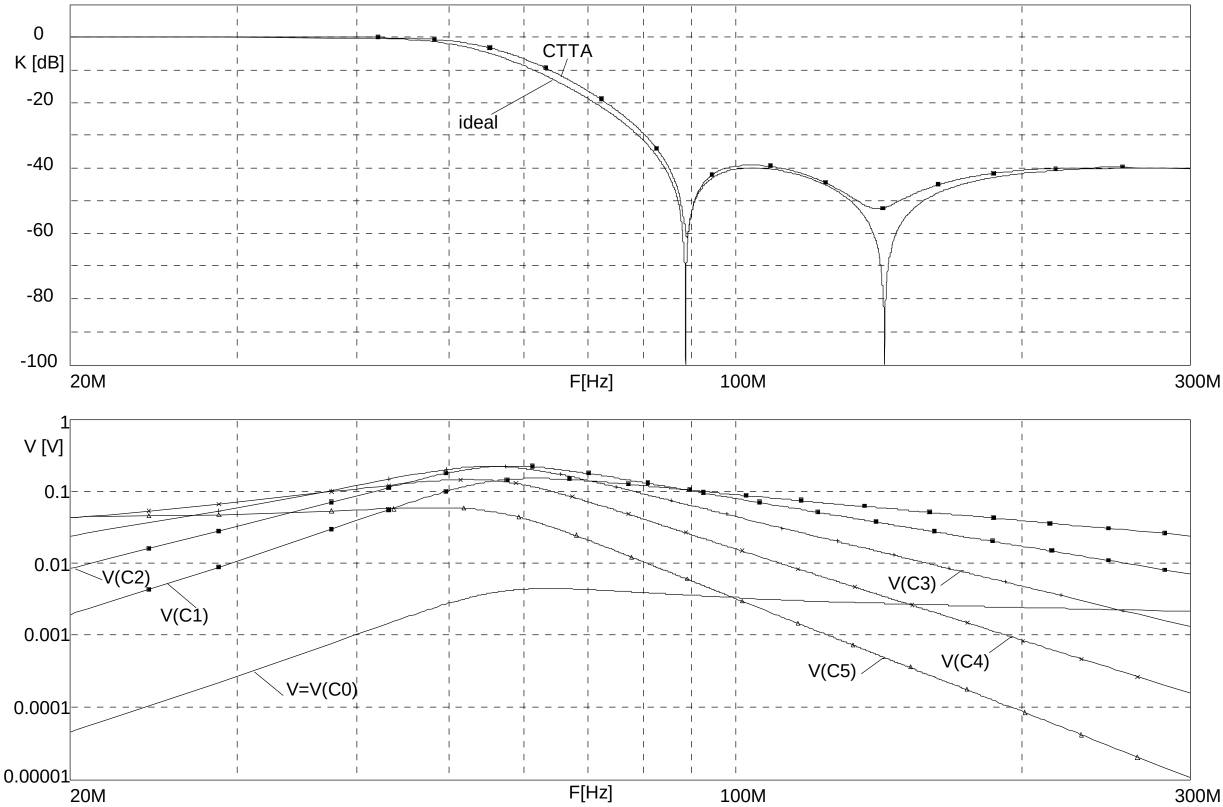

Fig. 4: Results of SPICE simulation of filter in Fig. 3.

6 Conclusions

The above filter structure, which is based on the simulation of arbitrary transfer function by generalized current divider, can be implemented both by described CTTA elements, and by the similar CDTAs with difference inputs. In the latter case, to sum output currents, we use not the input gate, but the *z*-outlets of CDTA elements.

Transconductances and working capacitances can easily be designed directly from the denominator coefficients of the transfer function. Some possible ways of subsequent filter optimization are also described. This optimization is effective in combination with computer simulation, with the utilization of CTTA or CDTA models [5,6]. Hitherto performed simulations offer satisfactory results for working frequencies about hundreds of MHz.

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Acknowledgments

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