A new building block for analog signal processing: current follower/inverter buffered transconductance amplifier

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Abstract—**A new active element for analog signal processing is proposed, namely the Current Follower/Inverter Buffered Transconductance Amplifier (CFBTA, CIBTA). This multi-terminal device is a synthesis of the well-known Current Differencing Buffered Amplifier (CDBA) and Current Differencing Transconductance Amplifier (CDTA). The common input stage of these amplifiers, the Current Differencing Unit (CDU), is replaced by a simpler current follower or inverter. Computer simulations and experiments based on commercially available integrated circuits demonstrate the usefulness of these elements for analog signal-processing filters.**

I. Introduction

In 1999 and 2003, two papers were published which introduced new circuit elements: CDBA (Current Differencing Buffered Amplifier) [1] and CDTA (Current Differencing Transconductance Amplifier) [2]. Both contain the so–called Current Differencing Unit (CDU) with two low-impedance terminals, *p* and *n*, and one high-impedance terminal, *z*. The difference of currents I_p and I_n flows out of the *z* terminal and the corresponding voltage drop on the external impedance is either copied by the voltage buffer to the *w* output of the CDBA or transformed by the Multiple-Output Operational Transconductance Amplifier (MO–OTA) to the *x*–terminal currents I_x of the CDTA.

Many applications of CDBA and CDTA in the analog signal processing area have been described in the literature, e.g. in [3–11] and in references cited therein. Their survey as well as a comparison of these universal blocks were summarized in [12]. In order to simplify the internal construction of both devices, the CDU can be replaced by a simple current follower or inverter. It is shown in [12] that the universality of the resulting element is still preserved when the output stage is represented by a multiple–output OTA, providing the currents of both directions.

In this paper, we propose an extension of the above approach: the conventional CDTA is modified such that the CDU is replaced by the current follower or inverter, and the *z*–terminal voltage is buffered by the voltage follower. The first modification simplifies the input stage, which improves the dynamic performance and power consumption, and the second one increases the circuit universality.

II. Circuit Description

The symbols and behavioral models of proposed active elements are in Fig. 1 (a) and (b). The corresponding circuit equations can be arranged in the following matrix form:

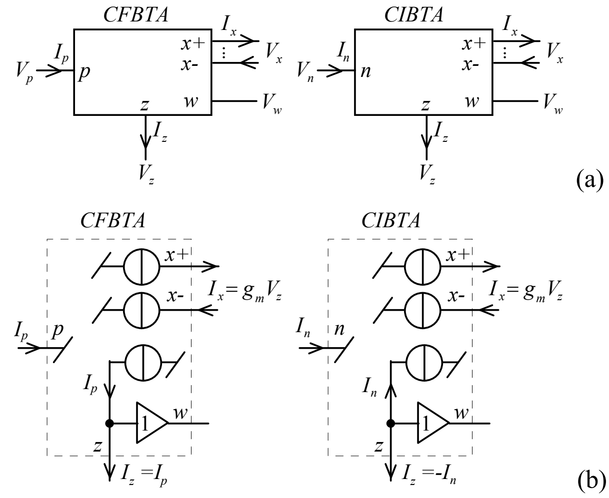

Fig. 1. (a) Symbol, (b) equivalent circuits of CFBTA and CIBTA.

$$\begin{pmatrix} I_z \\ V_w \\ I_x \\ V_{p(n)} \end{pmatrix} = \begin{pmatrix} 0 & 0 & 0 & (-)1 \\ 1 & 0 & 0 & 0 \\ g_m & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \end{pmatrix} \begin{pmatrix} V_z \\ I_w \\ V_x \\ I_{p(n)} \end{pmatrix}. \quad (1)$$

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According to the above Equations and equivalent circuits, the p and n input terminals behave as grounded because their voltages are zero. The z-terminal current is a copy of the p or n terminal current, flowing out of the device for CFBTA and into the device for CIBTA. Moreover, the z terminal voltage is copied to the low–impedance w terminal and transferred to the x terminal currents via the OTA transconductance g_m.

III. CIBTA IMPLEMENTATION

Fig. 2 shows a possible implementation of CIBTA using commercially available circuits, namely OPA860 [13], which consist of the so–called diamond transistors and the voltage buffers. The diamond transistor with B (base), C (collector) and E (emitter) terminals behaves as the current–controlled current conveyor (CC-CCII) [14] with the corresponding Y, Z, and X terminals [15]. When properly biased, the transconductance g_{mDT} of diamond transistor is of about 100 mA/V, ensuring a low input resistance of about 10 Ω of the n terminal in Fig. 2. The current I_n is conveyed to the collector of T_1 and flows into the z terminal in accordance with the definition of CIBTA. Transistors T_2 and T_3, forming the dual-output OTA, are complemented by the degeneration resistor $R_g >> 1/g_{mDT}$ in order to increase the OTA linearity. The transconductance of the OTA (g_m) is then given by the reciprocal value of R_g. When requiring only single–output OTA, T_3 can be omitted, with R_g grounded.

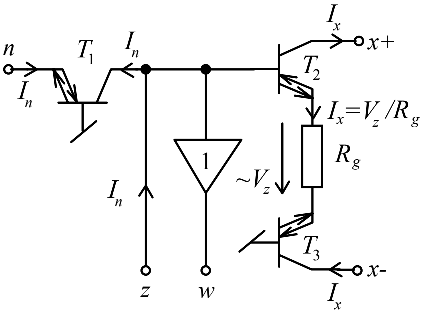

Fig. 2. Implementation of CIBTA using diamond transistors.

The circuit in Fig. 2 can be modified to CFBTA by adding one diamond transistor in front of T_1 in order to reverse the polarity of the input current.

IV. EXAMPLE OF CIBTA APPLICATION – BANDPASS FILTER

Fig. 3 (a) shows the schematic of 2nd–order bandpass filter employing one CIBTA with only one x terminal, two capacitors, and one resistor. The corresponding flow graph is in Fig. 3 (b). Its evaluation according to Mason's rule yields the following voltage transfer function:

$$K_{BP} = \frac{V_{BP}}{V_{in}} = -\frac{s\dfrac{1}{RC_1}}{s^2 + s\dfrac{1}{RC_2} + \dfrac{g_m}{RC_1C_2}}, \; g_m = \frac{1}{R_g}. \quad (2)$$

The natural frequency ω_0, bandwidth B and quality factor Q of the filter are given by the following formulae:

$$\omega_0 = \frac{1}{\sqrt{RR_gC_1C_2}}, \; B = \frac{1}{RC_2}, \; Q = \sqrt{\frac{R}{R_g}\frac{C_2}{C_1}}. \quad (3)$$

All the ω_0 and Q sensitivities to variations in the parameters of passive components are only 0.5 in magnitude. The B sensitivities to variations in R and C_2 are –1. The bandwidth is insensitive to parameters R_g and C_1.

Note that this filter has a greater application potential than indicated above. For example, when using the output terminal x instead of w, this voltage–mode filtering is switched from the bandpass to the highpass type.

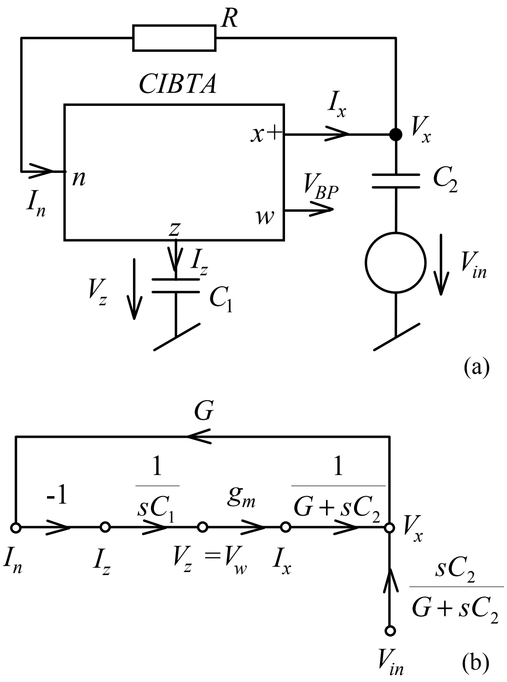

Fig. 3. (a) 2nd–order voltage-mode bandpass filter, (b) the corresponding flow graph. Here $G = 1/R$.

V. ANALYSIS OF NONIDEAL CASE

In reality, the non–ideal parameters of diamond transistors and buffers, particularly the parasitic impedances, affect the small–signal frequency response of the filter. Specifically, the parasitic impedances of the collector of diamond transistor and the input impedance of the buffer can play an important role. The values of their small-signal parameters are as follows [13]:

$$R_c = 54\text{ k}\Omega,\ C_c = 2\text{ pF},\ R_{buf}=1\text{ M}\Omega,\ C_{buf}=2.1\text{ pF}. \quad (4)$$

The equivalent circuit diagram of the filter from Fig. 3 (a), which respects the influence of the above parasitics, is shown in Fig. 4 (a). Because of the single x–type output of the CIBTA, the OTA stage is implemented by only one transistor. The R_B resistor is included according to the datasheet recommendation in order to reduce the effect of base input impedance [13]. The internal transconductances of the transistors are symbolized as additional resistances, which form, together with resistances of working resistors R and R_g, the equivalent resistances R' and R_g'.

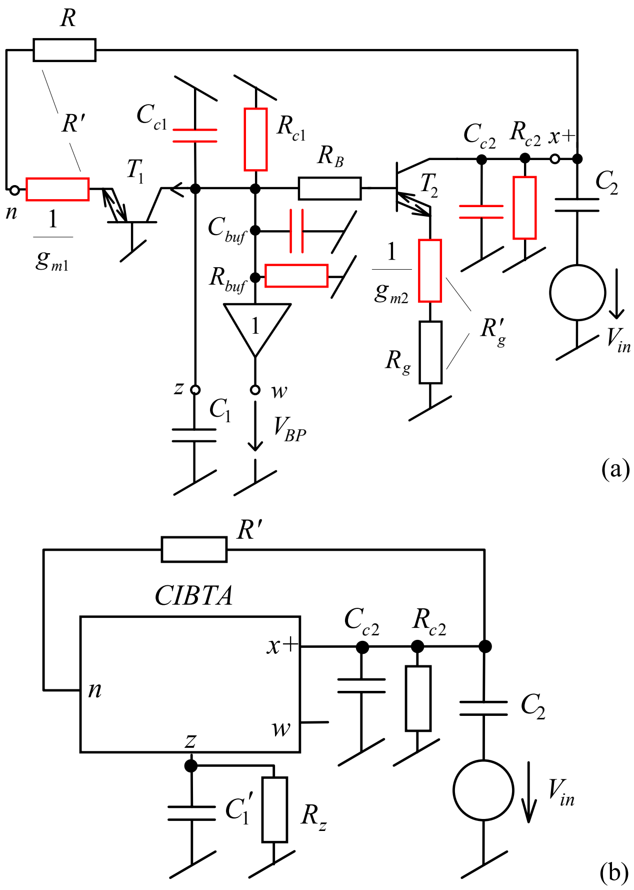

Fig. 4. (a) Filter from Fig. 3 implemented by the circuit from Fig. 2, with dominant parasitic impedances of diamond transistors and buffer, (b) the equivalent modification of the schematic from Fig. 3 (a).

As summarized in Fig. 4 (b), the effect of the above parasitic impedances consists in increasing the working capacitance C_1 to

$$C_1' = C_1 + C_{c1} + C_{buf}\,, \tag{5}$$

adding the z–terminal parasitic resistance

$$R_z = R_{c1} \& R_{buf} \approx 51.2\ \text{k}\Omega, \tag{6}$$

and the appearance of parasitic elements R_{c2}, C_{c2} at the x–terminal. In addition, resistances R and R_g are modified as described above.

The re-analysis of the model in Fig. 4 yields the modified transfer function:

$$\frac{V_w}{V_{in}} = -\frac{s\dfrac{C_2}{R'C_1'C_2'}}{s^2 + s\left[\dfrac{1}{R_x C_2'} + \dfrac{1}{R_z C_1'}\right] + \dfrac{1}{R'R_g'C_1'C_2'} + \dfrac{1}{R_z R_x' C_1'C_2'}}\,, \tag{7}$$

where

$$C_2' = C_2 + C_{c2}\,,\ R_x = R' \& R_{c2}\,. \tag{8}$$

Combining Eqs. (7) and (8) yields formulae for modified values of the natural frequency and the bandwidth:

$$\omega_0' = \frac{1}{\sqrt{R'R_g'C_1'C_2'}}\sqrt{1 + \frac{R_g'}{R_z}\left(1 + \frac{R'}{R_{c2}}\right)}\,, \tag{9}$$

$$B' = \frac{1}{R'C_2'} + \frac{1}{R_{c2}C_2'} + \frac{1}{R_z C_1'}\,. \tag{10}$$

The modified quality factor can be obtained as a ratio

$$Q' = \frac{\omega_0'}{B'}\,. \tag{11}$$

Eq. (9) shows two different reasons for modifying the natural frequency due to CIBTA non–idealities: (1) The trend of ω_0 decreasing owing to increasing filter capacitances and resistances, see the first part of Eq. (9). (2) The trend of ω_0 increasing due to the influence of finite values of resistances R_z and R_{c2}, see the second part of Eq. (9).

As shown in Section VI, the first tendency is dominant and thus one may expect the ω_0 to decrease. It is obvious from Eq. (10) that the modification of bandwidth is subject to similar rules with the dominant trend of increasing B due to the non–ideal effects. That is why the quality factor is less than in the ideal case. The differences can be reduced by choosing the working resistances R and R_g much smaller than the parasitic collector resistances.

VI. Experimental Results

The bandpass filter in Fig. 3 (a) was designed with the parameters f_0 = 1.3 MHz and Q = 1. The working resistances and capacitances were chosen as follows: $R = R_g$ = 1 kΩ, $C_1 = C_2$ = 120 pF. Then the corresponding theoretical value of f_0 from Eq. (3) is 1.326 MHz.

CIBTA was implemented by means of two OPA860s according to Fig. 2 with T_3 omitted (see also Fig. 4 a). A symmetrical power supply of ±5V was used. The bias currents for adjusting the internal transconductances of diamond transistors were adjusted by auxiliary resistors R_{ADJ} = 330 Ω, and R_B = 100 Ω was selected (see [13]). For PSpice simulation, the original model of OPA860 by Texas Instruments (Rev. B – Revised 4/25/06) was used. The filter was manufactured and its frequency response was measured using the network analyzer HP4195A. The input gate of the filter (V_{in}) was separated from the analyzer by unity-gain buffer (a part of OPA860), with 50 Ω matching resistor at the input. The impedance matching of the *w*– output of the filter and the circuit analyzer was solved similarly, by including a 50 Ω resistor in series with the voltage buffer.

Together with the frequency response, the frequency–dependent attenuation of the matching networks was also measured in order to subtract it and to obtain the real filter response. Then all the data measured were exported to the OrCAD PSpice 16 program such that the filter being measured was modeled by E–type controlled source, which is based on the FREQ–type look–up table. The results are in Fig. 5. The agreement between the simulated and measured characteristics is excellent. The measured and also simulated value of f_0 is 1.259 MHz, which is close to the frequency estimated from Eq. (9), i.e. 1.2935 MHz. This fact confirms the usefulness of the simple modeling of non-ideal effects according to Fig. 4.

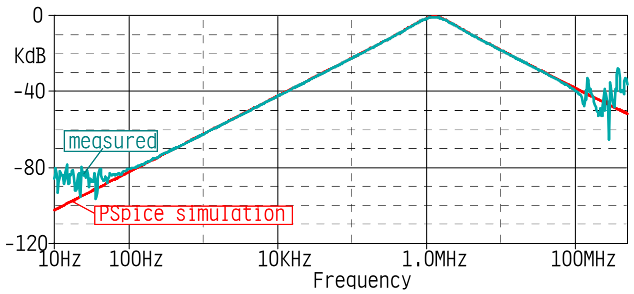

Fig. 5. Amplitude frequency responses of CIBTA–based bandpass filter from Fig. 3: simulated in PSpice and measured.

VII. CONCLUSIONS

The proposed novel active elements, CFBTA and CIBTA, represent two main improvements in comparison to the well–known CDBA and CDTA: 1) simplified input stage in the form of current follower or inverter, and 2) more universal output stage, containing both the multiple–output OTA for providing current outputs and the voltage buffer for supplying subsequent blocks with voltage–type signal. An example of CIBTA implementation from commercial ICs demonstrates the economical structure of the proposed elements. The above example of 2^{nd}–order filter implementation shows that, due to the availability of current and also voltage outputs, some applications can be synthesized with a reduced number of external components. The measurement results are consistent with theoretical assumptions and PSpice simulations.

ACKNOWLEDGMENT

The authors are thankful to the anonymous reviewers for their constructive comments and suggestions, which helped to improve the manuscript.

Research described in the paper was supported by the Czech Grant Agency under grant No. 102/09/1628, and by the research programmes of BUT No. MSM0021630503 and UD Brno No. MO FVT0000403, Czech Republic.

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