A Novel First-Order Current-Mode All-Pass Filter Using CDTA

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Abstract. *This paper presents a new realization of a first-order current-mode (CM) all-pass filter (APF) using the recently proposed modern active building block (ABB), namely the current differencing transconductance amplifier (CDTA). The CM APF is made using minimum number of components, namely a single CDTA and one grounded capacitor. The circuit does not use any external resistors and offers the advantages of current-tunable pole frequency, low input impedance and high output impedance. Non-ideal analysis and sensitivity analysis are provided and PSPICE simulation results are included to verify the workability of the circuit.*

Keywords

Current-mode (CM), active building block (ABB), all-pass filter (APF), Current Differencing Transconductance Amplifier (CDTA).

1. Introduction

The recently proposed current-mode (CM) active building block (ABB), namely the current differencing transconductance amplifier (CDTA) [1], has been found to be versatile for CM signal processing and its use has reportedly provided several circuit solutions. These primarily consist of the design of CM filters [2], [3], [4], [5] and sinusoidal oscillators (including quadrature and multi-phase oscillators) [6], [7], [8], [9], [10]. The motivation of this paper is to propose a minimum component CDTA based first-order CM all-pass filter (APF). APFs are very important circuits for many analog signal processing applications and are used, generally, in phase equalization and for introducing a frequency dependent delay while keeping the amplitude of the input signal constant over the desired frequency range [11].

CDTA based first-order CM APFs have been proposed earlier in [12], [13], [14]. However, the circuits proposed in [12] and [13] use an external linear resistor and do not provide any electronic tunability of the pole frequency: "Due to the on-going trends to lower supply voltages and maintain low-power operations, linear resistors have become too large for on-chip integration in ultra-low-power environments and hence, their use should be avoided" [15]. The virtually grounded capacitors in [12] and [13], are also floating in the non-ideal sense. Although the CM-APF circuit proposed in [14] is "resistor-less", it uses two ABBs and a floating capacitor (in the non-ideal case). Apart from CDTA, a very rich catalogue of CM APFs using different ABBs also exists in the literature [16], [17], [18], [19], [20], [21], [22], [23], [24], [25]. However, a close investigation of the literature reveals that the proposed circuits suffer from the following weaknesses:

1. Excessive number of passive components (three or more) in [17], [18], [19], [22], [23],
2. use of floating capacitors in [17], [20], [24], which is not desirable for IC implementation,
3. non-availability of the current-output from a high output impedance terminal in [20], [21], [24],
4. use of multiple ABBs in [18], [23] and
5. no inherent electronic tuning properties in [16], [17], [18], [19], [20], [21], [22], [23], [25].

With this background, a new circuit is proposed here, which overcomes the above drawbacks. The proposed circuit uses a minimum number of components, namely one ABB and one grounded capacitor. A modified CDTA, called ZC-CDTA (Z-copy CDTA) [26], has been used as the ABB and the proposed circuit offers the following advantages:

1. Canonic number of components is employed to realize a CM APF and the use of grounded capacitors further makes the circuit suitable for monolithic integration as grounded capacitor circuits can compensate for the stray capacitances at their nodes [27], [28],
2. current-tunable pole frequency by means of the external bias current,
3. low input impedance and high output impedance make the circuit suitable for cascading to synthesize higher-order filters and
4. good active and passive sensitivities of the pole frequency and gain of the filter.

With all the above stated advantages, the proposed circuit is a novel addition to the present repertoire of CM APFs and applications of CDTA. The characteristics of the ABB (ZC-CDTA) are discussed in the following section, followed by the proposed CM APF circuit and finally, PSPICE circuit simulations are included to verify the workability of the proposed circuit.

2. Proposed Circuit

A Z-copy current differencing transconductance amplifier (ZC-CDTA) is an ABB, ideally characterized by the following equations

$$V_p = V_n = 0, \quad I_z = I_{z_c} = I_p - I_n, \qquad (1)$$
$$I_{x+} = g_m V_z, \quad I_{x-} = -g_m V_z$$

where g_m represents the transconductance and is a function of the bias current. The circuit symbol of ZC-CDTA is shown in Fig. 1 and a possible bipolar implementation of the circuit using [9] is shown in Fig. 2.

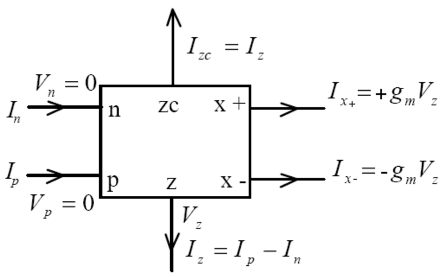

Fig. 1. Symbolic representation of ZC-CDTA.

A ZC-CDTA with three x terminals, along with one grounded capacitor is used to create a first-order CM APF, as shown in Fig. 3. Using (1), a routine analysis of the circuit yields the following transfer function

$$T(s) = \frac{I_o}{I_{in}} = \frac{sC - g_m}{sC + g_m} . \qquad (2)$$

Clearly, the ideal transfer function $T(s)$ has a unity gain and a frequency dependent phase given by

$$\angle T(j\omega) = \pi - 2tan^{-1}(\frac{\omega C}{g_m}) . \qquad (3)$$

The angular pole frequency $\omega_o = \frac{g_m}{C}$ is tunable by means of the bias current. Instead of using a ZC-CDTA with three x terminals, another ZC-CDTA variant could be used to create the circuit. This variant has two different internal transconductances g_{m1} and g_{m2} controlled by bias currents I_{B1} and I_{B2}, respectively. A possible implementation of this ZC-CDTA variant using second-generation current conveyors (CCIIs) and operational transconductance amplifiers (OTAs) [1] is shown in Fig. 4. The CM APF created using this ZC-CDTA variant is shown in Fig. 5 and a routine analysis of the circuit yields the following transfer function

$$\frac{I_o}{I_{in}} = \frac{sC - g_{m2}}{sC + g_{m1} - g_{m2}} . \qquad (4)$$

It is evident from (4) that for the APF operation, the transconductances have to satisfy the following condition

$$g_{m1} = 2g_{m2} \qquad (5)$$

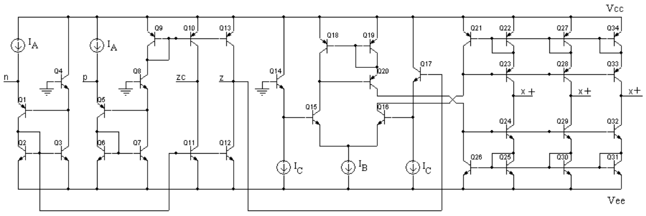

Fig. 2. A possible bipolar implementation of ZC-CDTA.

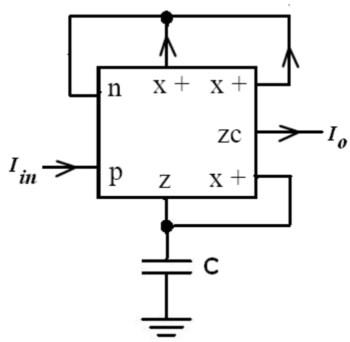

Fig. 3. Proposed first-order CM APF.

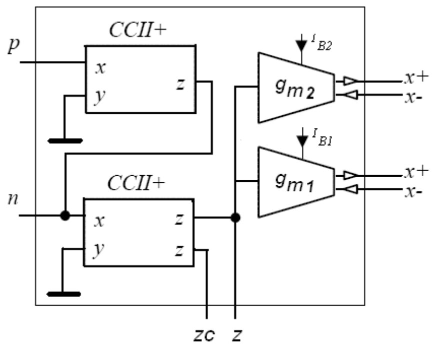

Fig. 4. A possible implementation of the modified ZC-CDTA using CCIIs and OTAs.

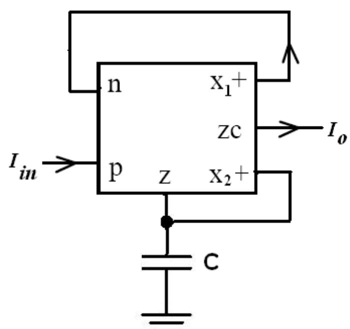

Fig. 5. CM APF using a modified ZC-CDTA.

Hence, the input bias currents I_{B1} and I_{B2} have to be varied accordingly and the circuit suffers from critical current matching conditions. Moreover, any desired change in the angular pole frequency by means of the bias current I_{B2}

is not independent, since I_{B1} has to be simultaneously varied to satisfy the condition of operation. Hence, the APF in Fig. 3 seems to be a preferable circuit solution as it is free from any input matching constraints. The non-ideal analysis of the circuit in Fig. 3 is discussed in the following section.

3. Non-Ideal Analysis

For a complete analysis of the circuit, it is important to take into account the following non-idealities of CDTA (as pointed in [13]):

1. $$I_z = \alpha_p I_p - \alpha_n I_n, \quad I_{z_c} = \beta I_z \tag{6}$$
   where α_p, α_n are the parasitic current transfer gains from p, n to z terminal, respectively and β is the parasitic current transfer gain from z terminal to z_c terminal. All these gains slightly differ from their ideal values of unity by current tracking errors.
2. The non-zero parasitic input impedances at terminals p and n of the CDTA are represented by R_p and R_n.
3. The use of multiple x output terminals produces errors in the copies of the currents. The bipolar implementation of the circuit using transistors with high current-emitter gain and/or use of good bipolar mirrors (e.g. with base-current compensation) to generate the multiple copies of x currents, may alleviate the problem. An accurate method of current tracking and providing multiple copies of a current could be found in [30] (Section 3.3). In this paper we use a bipolar realization of CDTA as provided in [9] which uses Wilson current mirrors in place of simple current mirrors and thereby reducing the tracking errors [31]. We model the variations/mismatch between the currents at x terminals, such that $\gamma_1 g_m$ is the transconductance gain from the z terminal to the x terminal connected to capacitor and $\gamma_2 g_m$ & $\gamma_3 g_m$ are the transconductance gains from the z terminal to the x terminals connected to the n terminal CDTA. In the ideal case $\gamma_1 = \gamma_2 = \gamma_3 = 1$, but in the non-ideal case these values slightly differ from unity by current tracking errors.
4. The parasitic resistance R_z and parasitic capacitance C_z appear between the high-impedance z terminal of the CDTA and ground. Although the stray/parasitic capacitance C_z can be absorbed into the external capacitor as it appears in shunt with it, the presence of parasitic resistance at terminal z would change the type of the impedance which should be of a purely capacitive character.
5. The parasitic impedances appearing between the high-impedance x terminals of the CDTA and ground. For simplicity, the parasitic impedances for each of the three x terminals are taken to be same, with parasitic resistance as R_x and parasitic capacitance as C_x.

Considering all the above non-ideal effects, the transfer function of the CM APF shown in Fig. 3 gets modified to

$$T(s) = \frac{I_o}{I_{in}} = \tag{7}$$

$$= \frac{\alpha_p \beta (s(C + C_z + C_x) + \frac{1}{R_z} + \frac{1}{R_x} - \gamma_1 g_m)}{s(C + C_z + C_x - 2\alpha_n C_x) + \frac{1}{R_z} + \frac{1-2\alpha_n}{R_x} + g_m(\alpha_n(\gamma_2 + \gamma_3) - \gamma_1)}.$$

It is evident from (7) that the effect of parasitic impedances is subtractive in the denominator, but additive in the numerator. If g_m is sufficiently higher than $\frac{1}{R_z} + \frac{1}{R_x}$ and $C \gg (C_z + C_x)$ and , then (7) could be approximated to

$$\frac{I_o}{I_{in}} \approx \frac{\alpha_p \beta (sC - \gamma_1 g_m)}{sC + g_m(\alpha_n(\gamma_2 + \gamma_3) - \gamma_1)} \tag{8}$$

This approximated transfer function now, has a frequency dependent phase given by

$$\angle T(j\omega) = \pi - tan^{-1}(\frac{\omega C}{\gamma_1 g_m}) - tan^{-1}\Big(\frac{\omega C}{g_m(\alpha_n(\gamma_2 + \gamma_3) - \gamma_1)}\Big). \tag{9}$$

It is clear from (8) and (9), that both gain and phase of the filter are affected by the parasitic current transfer gains and hence a good design of CDTA (as in [9]) should be considered to alleviate the non-ideal effects. The sensitivity of the angular "pole" frequency (ω_p) to the non-idealities and external component is given as

$$S^{\omega_p}_{R_n, R_p, \alpha_p, \beta} = 0, \quad S^{\omega_p}_{g_m} = 1, \quad S^{\omega_p}_{C} = -1, \tag{10}$$

$$S^{\omega_p}_{\alpha_n} = \frac{\alpha_n(\gamma_2 + \gamma_3)}{\alpha_n(\gamma_2 + \gamma_3) - \gamma_1}, \tag{11}$$

$$S^{\omega_p}_{\gamma_1} = \frac{-\gamma_1}{\alpha_n(\gamma_2 + \gamma_3) - \gamma_1}, \quad S^{\omega_p}_{\gamma_2} = \frac{\alpha_n \gamma_2}{\alpha_n(\gamma_2 + \gamma_3) - \gamma_1},$$

$$S^{\omega_p}_{\gamma_3} = \frac{\alpha_n \gamma_3}{\alpha_n(\gamma_2 + \gamma_3) - \gamma_1}\ . \tag{12}$$

The sensitivity of the angular "zero" frequency (ω_z) to the non-idealities and external component is given as

$$S^{\omega_z}_{R_n, R_p, \alpha_p, \alpha_n, \beta, \gamma_2, \gamma_3} = 0, \quad S^{\omega_z}_{g_m, \gamma_1} = 1, \quad S^{\omega_z}_{C} = -1\ . \tag{13}$$

It should be noted that in the non-ideal case, the angular "pole" frequency (that of the denominator) is different from the corresponding angular "zero" frequency (that of the numerator) and thus this mismatch affects both the magnitude and phase response of the circuit. Only under the condition that $\alpha_n(\gamma_2 + \gamma_3) = 2\gamma_1$, the gain of the filter corresponding to the approximated transfer function in (8), can be taken as

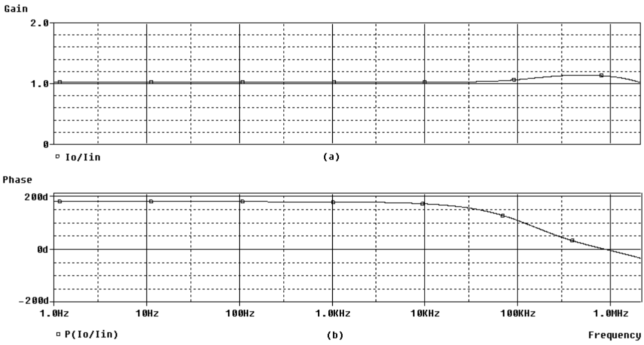

Fig. 6. (a) The magnitude response of the all-pass filter, (b) the phase response of the all-pass filter.

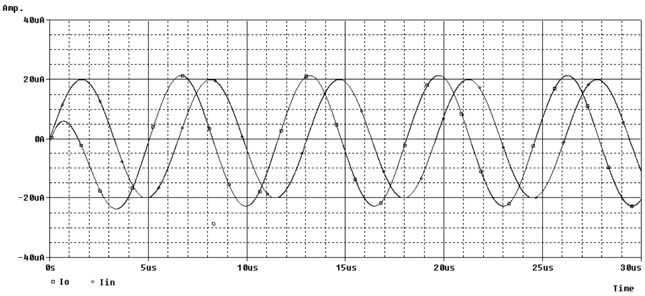

Fig. 7. Time-domain response of the proposed all-pass filter.

NR100N: NPN (IS=121E-18, BF=137.5, VAF=159.4, IKF=6.974E-3, ISE=36E-16, NE= 1.713, BR=0.7258, VAR=10.73, IKR=2.198E-3, RE=1, RB=524.6, RBM=25, RC=50, CJE=0.214E-12, VJE=0.5, MJE=0.28, CJC=0.983E-13, VJC=0.5, MJC=0.3, XCJC=0.034, CJS=0.913E-12, VJS=0.64, MJS=0.4, FC=0.5, TF=0.425E-8, TR=0.5E-8, EG=1.206, XTB=1.538, XT1=2)
PR100N: PNP (IS=73.5E-18, BF=110, VAF=51.8, IKF=2.359E-3, ISE=25.1E-16, NE=1.650, BR=0.4745, VAR=9.96, IKR=6.478E-3, RE=3, RB=327, RBM=24.55, RC=50, CJE=0.18E-12, VJE=0.5, MJE=0.28, CJC=0.164E-12, VJC=0.8, MJC=0.4, XCJC=0.037, CJS=1.03E-12, VJS=0.55, MJS=0.35, FC=0.5, TF=0.610E-9, TR=0.610E-8, EG=1.206, XTB=1.866, XT1=1.7)

Tab. 1. NR100N and PR100N transistor parameters

$K = \alpha_p \beta$. In that case, the sensitivity of all-pass filter gain (K) [29] to the non-idealities and external component can be analyzed as

$$S^K_{R_n,R_p,C,\alpha_n,\gamma_1,\gamma_2,\gamma_3,g_m} = 0, \quad S^K_{\alpha_p,\beta} = 1 \tag{14}$$

It is evident from (10) – (14) that all the sensitivity values are no more than unity in magnitude and unlike in [12] and [13], the angular pole frequency is insensitive to the parasitic resistances R_p and R_n. Hence, the circuit exhibits a good sensitivity performance. However, an exception to this is the ω_p sensitivity to α_n, which implies that the angular pole frequency is highly sensitive to this non-ideality. As pointed in [13] and [29], the parasitic current gains α_p, α_n and β are frequency-dependent with a first-order low-pass roll-off, the cut-off frequency dependent on the devices and the technology used in implementing the ABB. The high frequency performance/potential is, therefore, limited by the actual circuit parameters and the technology used. The parasitic current transfer gains from terminal z to z_c and in creating copies of currents from multiple x terminals, could be reduced/eliminated by the method proposed in [30], where multiple copies of a current could be generated with accurate current tracking. The method, however, requires the use of a low value auxiliary resistor within the CDTA.

4. Brief Discussion

The circuits proposed in this paper use a single ZC-CDTA / modified CDTA with multiple x terminals and one grounded capacitor to realize a first-order CM APF. As pointed in the previous sections, the circuits suffer matching/cancellation constraints and require a good design of CDTA (e.g. [9]) to alleviate the non-ideal effects. However, matching constraints/conditions are also present in most of the counterparts, as in [17], [18], [19], [23], [24]. The previously reported APFs which do not require any critical matching conditions as in [12], [13], [16], [9] and [25], however, do not provide any inherent electronic tuning properties. Thus, there is a trade-off. A resistor-less CM APF using a single CDTA or any other ABB, one true grounded capacitor (not virtually grounded) and no matching constraints, is yet to be reported in the literature. Creating such a CM APF is in no way trivial and analog circuit designers and researchers in the field should consider it as a challenging problem.

5. Simulation Results

The proposed CM APF shown in Fig. 3 is simulated in PSPICE using the bipolar implementation of CDTA as provided in Fig. 2. The process parameters for PR100N and NR100N bipolar transistors of ALA400 transistor array from AT&T [32] have been used with ± 2.5 V voltage supply. The transistor parameters have been shown in Tab. 1. The circuit was designed with $C = 1$ nF and with the bias currents $I_A = I_B = 50$ μA and $I_C = 25$ μA. It is evident from the bipolar implementation shown in Fig. 2, that the transconductance $g_m = \frac{I_B}{2V_T}$, where V_T is the thermal voltage whose value is approximately 26 mV at 27°C. With $I_B = 50$ μA, the transconductance is set at 0.96 mS and the ideal value of the pole frequency ($\omega_o = \frac{g_m}{C}$) is 153.1 kHz. Although, the design would vary with the change in operating temperature, but this, however, should not be considered as a drawback, as the designer has an electronic control over the circuit parameters through the bias current [29].

The magnitude gain response and phase response of the filter are shown in Fig. 6(a) and Fig. 6(b) respectively. The time-domain response of the proposed APF is shown in Fig. 7. A sine wave of 20 μA amplitude and 153.1 kHz is applied as the input to the filter and the output is 89.6° phase-shifted, which is in correspondence with the theoretical value of 90°.

6. Conclusions

A novel first-order current-mode all-pass filter using current differencing transconductance amplifier (CDTA) is presented. The circuit structure is canonic and consists of one Z-copy CDTA (ZC-CDTA) and one grounded capacitor. The circuit offers the advantages of monolithic integration, current tunability of the pole frequency, low input impedance, high output impedance and good sensitivity performance. PSPICE simulation results have verified the workability of the circuit.

Acknowledgements

The authors would like to thank Prof. Dr. Raj Senani, Director, Netaji Subhas Institute of Technology (NSIT), India, for being a catalyst behind their work.

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