All-Pass Filters in Current Mode

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Abstract. *Analogue first, second and high-order all-pass active filters in the current mode, with constant group delay and magnitude responses, are presented in this paper. These filters are based on a modification of the multi-loop feedback canonical structures using signal flow graphs. Implementations by multi-output transconductors, namely classical OTAs and novel CDTAs are given.*

Keywords

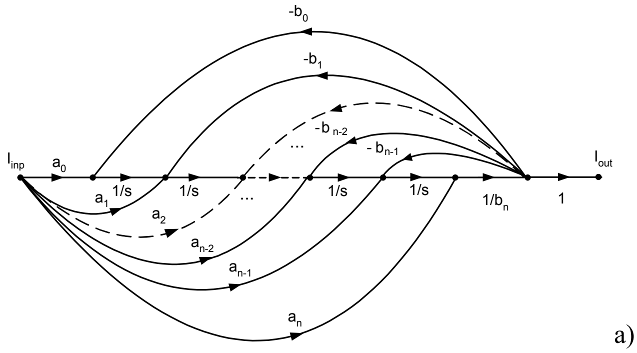
Analogue circuits, all-pass filters, current mode, multi-loop structures, transconductors.

1. Introduction

The all-pass filter (APF) [1] is a special type of network, whose magnitude response is constant, but the phase is linearly frequency-dependent and/or the group delay is constant in some frequency range. A lot of publications have been written about active APFs in the standard voltage mode using opamps, but a few [7], [9] about APFs in the current mode (CM) [2], which is the reason for writing this paper.

Analogue active filters in the CM have recently received substantial attention. It is well known [1] that they offer higher frequency performances and a large dynamic range, operate at lower DC supply, can be easy to design and made integrable using modern IC technologies. It can be simply implementing there such operation as current summation or subtraction (a node only), current distribution (replicas using current mirrors) and current integration. More outputs with independent loading are there too. The feature CM filters have found many applications in audio, video and communication systems.

Research [2] – [7] has shown the great success of the filters based on the OTA-C approach. It is due to a simple implementation of the operational transconductance amplifiers (OTA) and grounded capacitors (C) only. Many OTA-C filter configurations and structures have been investigated, mostly in the early works with single output OTAs [3], then with double (balance) output ones [4] and recent papers deal with multiple-output OTAs. In [7] OTAs with differential input and triple-output are used. The multiple-output transconductors give more possibilities in filter design. In this paper a suitable modification and direct circuit implementation of the CM multi-loop feedback (MLF) structures given in [6] will be shown. Beside standard OTAs, the novel multiple-output current-differencing-input transconductors (CDTA) from [8] are used too. For our synthesis the corresponding signal flow graph (SFG) technique and approach from [6] will be applied. The design procedure given here is general, simpler and more obvious than it was in [7].



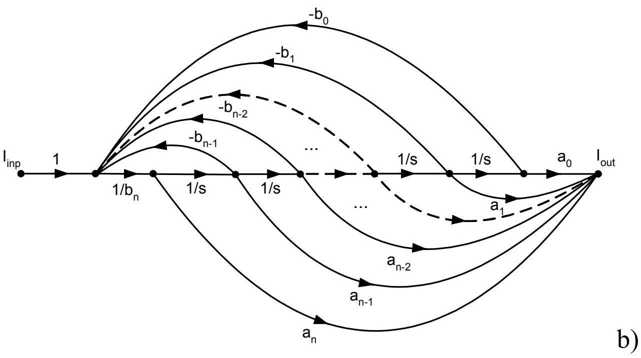


Fig. 1. Basic signal flow graphs of the multi-loop structures in the current mode.
a) the first canonical analogue structure,
b) the second canonical analogue structure.

2. APF Structures in Current Mode

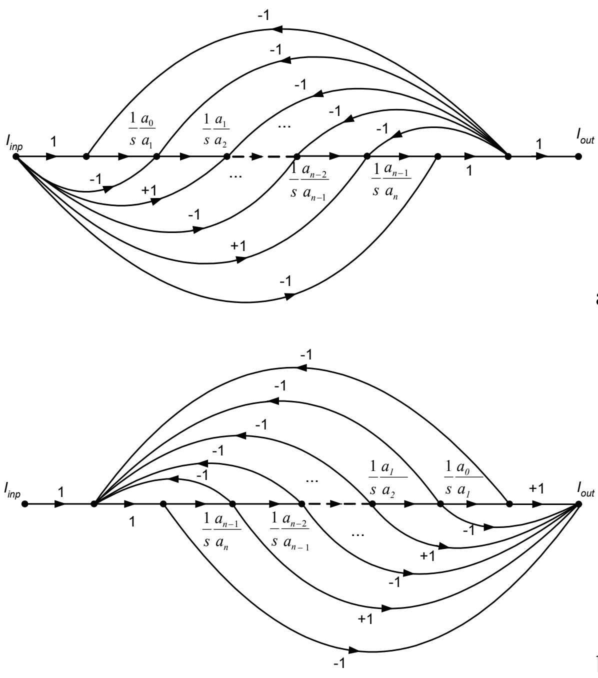
The current transfer function of any n^{th}-order all-pass filter is generally expressed by the following formula

$$K = \frac{I_{out}}{I_{inp}} = \frac{a_0 - a_1 s + a_2 s^2 - a_3 s^3 \ldots \pm a_n s^n}{a_0 + a_1 s + a_2 s^2 + a_3 s^3 \ldots + a_n s^n} \quad . \quad (1)$$

Transfer function (1) can be directly implemented by one of the state-variable MLF structures, which is in the classical VM well known [2].

The basic SFGs of two suitable MLF structures in the CM are given in Fig. 1, namely the first canonical MLF structure (Fig. 1a) and the second canonical one (Fig. 1b). Note that these analogue structures are in the literature known as the inverse follow-the-leader feedback (IFLF) with input distribution (Fig. 1a) and follow-the-leader feedback (FLF) with output summation (Fig. 1b), respectively.

A circuit realization of both the basic SFGs (Fig. 1) requires these types of building blocks: current integrators (realizing branches 1/s), current multipliers by constant (realizing branches a_i, b_i), current distributors (realizing the spring nodes) and current summers (realizing the hole nodes), which is a little complicated and it is the reason of the following modification.



a)

b)

Fig. 2. Modified signal flow graphs of the multi-loop structures convenient for n^{th}-order all-pass filter in the current mode:
a) the first canonical analogue structure,
b) the second canonical analogue structure.

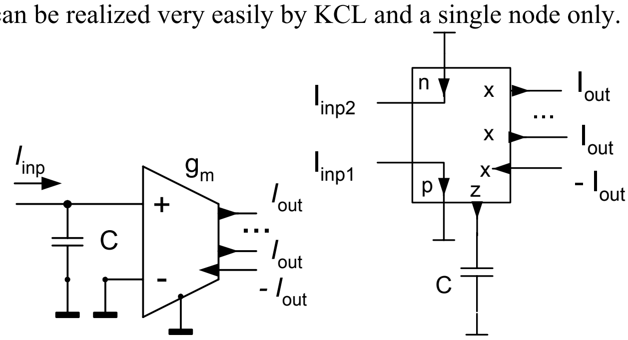
For better and simpler circuit implementation the SFGs from Fig. 1 can be modified, as was shown in detail in [6]. The resulting forms convenient for the n^{th}-order APF are in Fig. 2, namely the modified first (Fig. 2a) and second (Fig. 2b) canonical structure. Both these graphs are directly corresponding with formula (1) and have the gains of more branches equal to ±1 (to be easy circuitry realized, by connection) and the desired coefficients (a_i) are in the transfer function of the integrators only, then there are no multipliers.

3. Building Blocks for APF-CM

The circuit realization of the modified SFGs (Fig. 2) requires only two types of active building block, namely the current distributors (CD) and the current integrators (CI). Note that the **adder** of the currents

$$I_{out} = \sum_{i}^{n} I_{inp} \, , \tag{2}$$

can be realized very easily by KCL and a single node only.



a) b)

Fig. 3. Multi-output current integrators.
a) using OTA-SIMO,
b) using CDTA-CDIMO.

The **current integrator** with desired transfer function

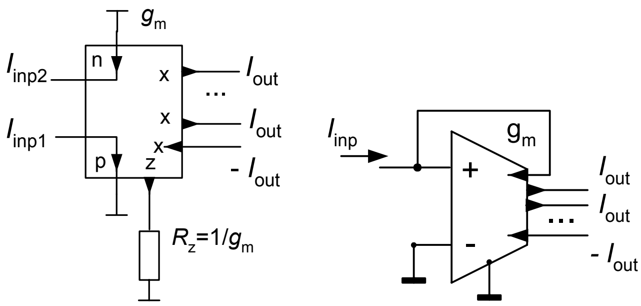
$$K_i = \frac{I_{out}}{I_{inp}} = \frac{1}{s}\frac{a_n}{a_{n+1}} \, , \tag{3}$$

can be implemented by single-input multiple-output (SIMO) transconductor (OTA) and capacitor (C) as shown in Fig. 3a. There are more current replicas with opposite phase, given by the following formula

$$I_{out} = \pm \frac{1}{s}\frac{g_m}{C} I_{inp} \, . \tag{4}$$

Note that the opposite phase of the I_{out} is required in some applications of the APF structure (Fig. 2b).

The other CI with the novel current-differencing-input multiple-output (CDIMO) transconductor (CDTA) [8] is shown in Fig. 3b. There the output currents are given by formula (4) where $I_{inp}=I_{inp1}-I_{inp2}$. The lossy integrator can be obtained putting at the port (z) a parallel connection RC.



a) b)

Fig. 4. Multi-output current distributors:a) using CDTA-CDIMO, b) using OTA-SIMO.

The **current distributor**, producing n current replicas of the input current, can be realized using the CDTA-CDIMO as shown in Fig. 4a, putting at the port (z) a grounded resistor, with the value $R_z = 1/g_m$, where g_m is the transconductance of the CDTA. A simpler CD using the OTA- SIMO is shown in Fig. 4b. Note that the CD is a current follower with more outputs (inverting and/or non-inverting) and with current-differencing input.

4. Circuit Realization of the APF-CM

The circuit realization of the SFG from Fig. 2a, modeling the first canonical structure of the APF in the CM, is shown in Fig. 5a. There are two current distributors (CD) realizing n replicas of the input or output (feedback) currents and corresponding to spring nodes. The n integrators (CI) connected in cascade have only one output and on their input is the summation of direct and feedback currents.

The circuit implementation of the second canonical structure following from the SFG given in Fig.2b is simpler. There is the output summation, which in the CM is very easy to realize by output node only. The integrators (CI) have three outputs producing the required current replicas. The current distributor (CD-1) is realizing two replicas of the input current. On the input of the CD-1 is the summation of exciting and feedback currents.

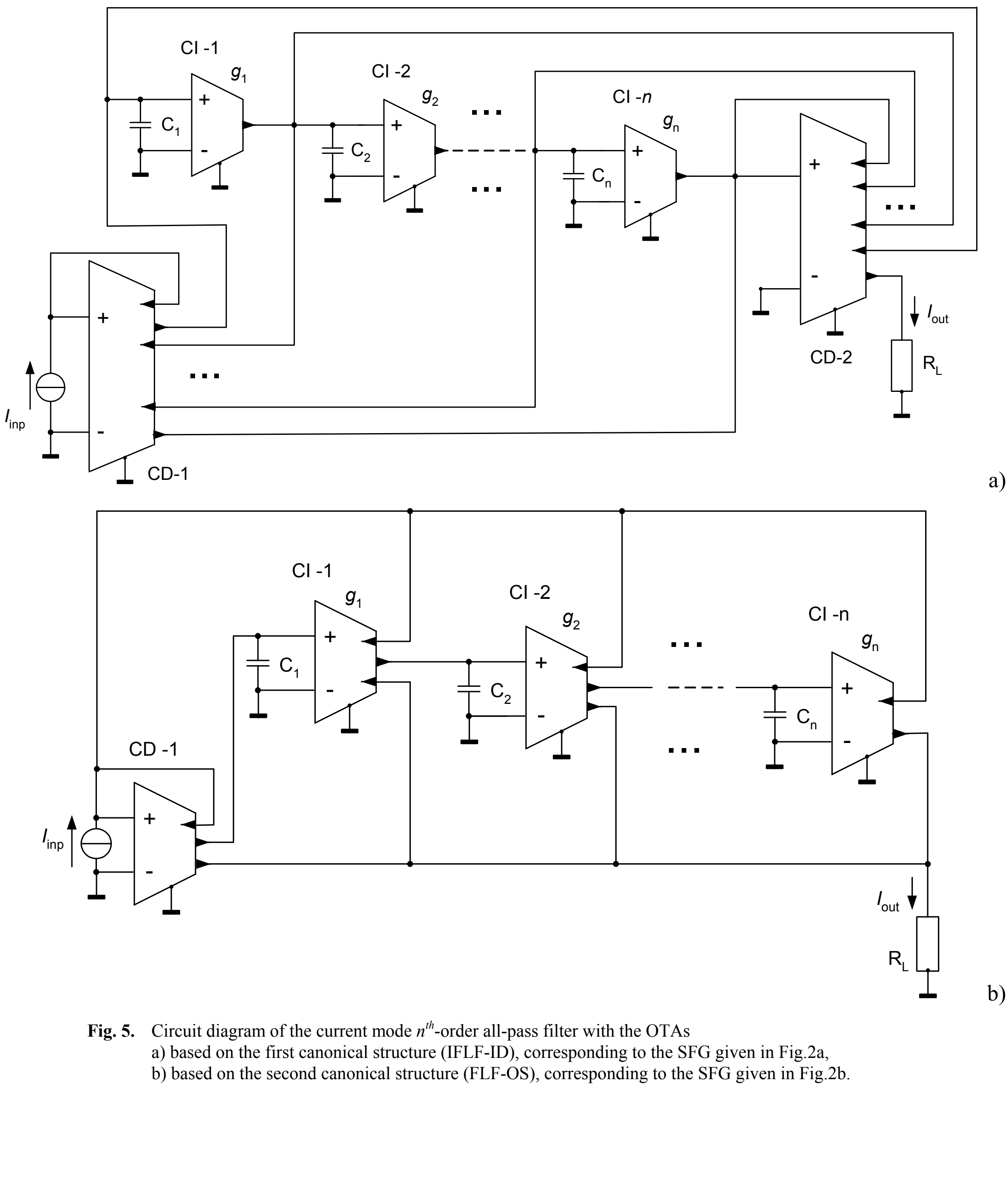


Fig. 5. Circuit diagram of the current mode n^{th}-order all-pass filter with the OTAs
a) based on the first canonical structure (IFLF-ID), corresponding to the SFG given in Fig.2a,
b) based on the second canonical structure (FLF-OS), corresponding to the SFG given in Fig.2b.

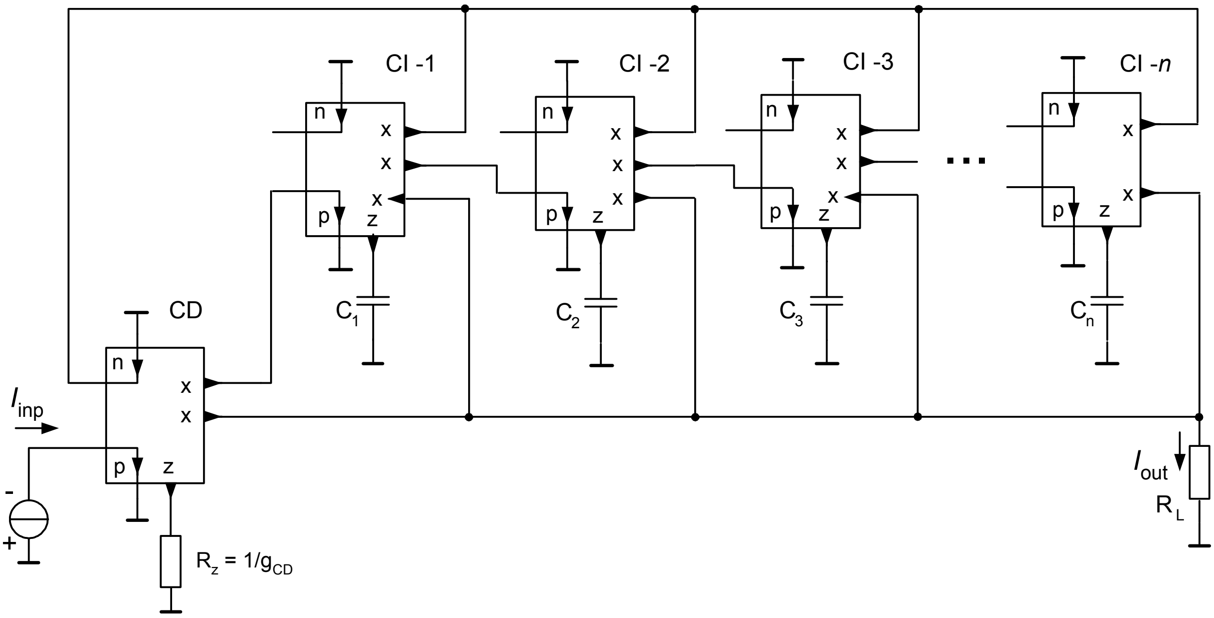


Fig. 6. Circuit diagram of the current mode n^{th}-order all-pass filter with the CDTAs based on the second canonical structure (FLF-OS), corresponding to the SFG given in Fig.2b.

5. First-Order APF-CM

The first-order all-pass transfer function in the CM is generally defined as

$$K(s) = \frac{I_{out}}{I_{inp}} = \pm\, k \frac{a_0 - a_1 s}{a_0 + a_1 s} = \pm\, k \frac{\omega_0 - s}{\omega_0 + s}. \tag{5}$$

Transfer function (5) can be implemented by the circuits shown in Fig. 7. The simpler first-order APF in Fig. 7a was first given in [9] and has the following parameters, namely the frequency responses

$$\left|K(j\omega)\right| = k, \quad \varphi(\omega) = -2\; artg \frac{\omega}{\omega_0}\;, \tag{6}$$

and the group delay

$$\tau(\omega) = \frac{2}{\omega_0} \frac{1}{1 + \left(\dfrac{\omega}{\omega_0}\right)^2}, \quad \tau(0) = \frac{2}{\omega_0}, \quad \tau(\omega_0) = \frac{1}{\omega_0}. \tag{7}$$

If $R_Z = g_m^{-1}$, then the basic gain (k) and the characteristic angular frequency (ω_0) are

$$k = g_m R_L = 1, \qquad \omega_0 = \frac{1}{RC} \cdot \tag{8}$$

A little complicated, but with all grounded passive elements and smaller influence of parasitic capacitances is the first-order all-pass filter with two CDTAs shown in Fig. 7b. There the basic gain is also unity (k = 1) and the characteristic angular frequency is now given by

$$\omega_0 = \frac{g_m}{C}, \tag{9}$$

which gives the possibility to electronically control this filter by an auxiliary DC current (I_{set}), controlling the transconductance g_m.

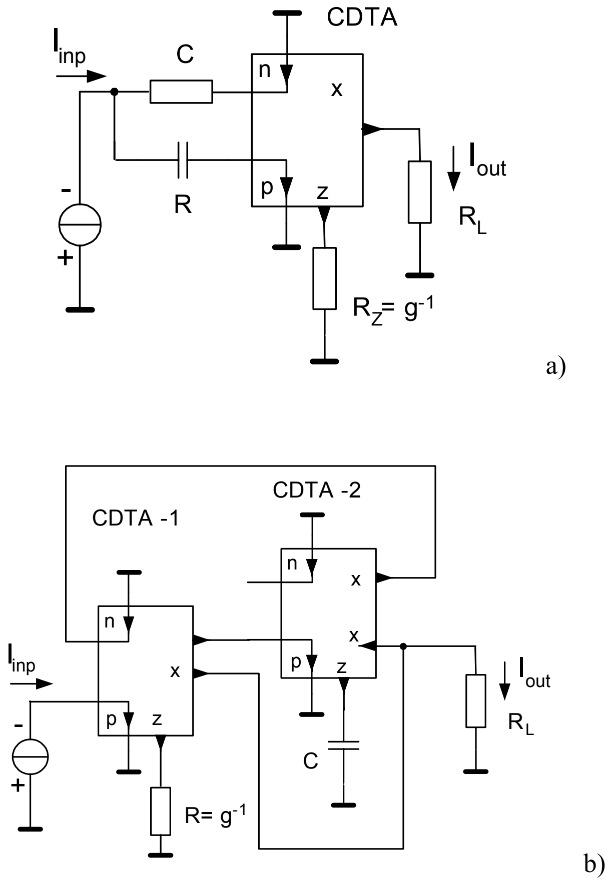


Fig. 7. First-order all-pass filters with the CDTAs.

6. Second-Order APF-CM

The second-order all-pass transfer function in the CM is generally defined as

$$K(s) = \frac{I_{out}}{I_{inp}} = \pm k \frac{a_0 - a_1 s + a_1 s^2}{a_0 + a_1 s + a_1 s^2}. \tag{10}$$

Formula (10) can be implemented by cascading two first-order all-pass filters from Fig. 7, which is properly described in [9].

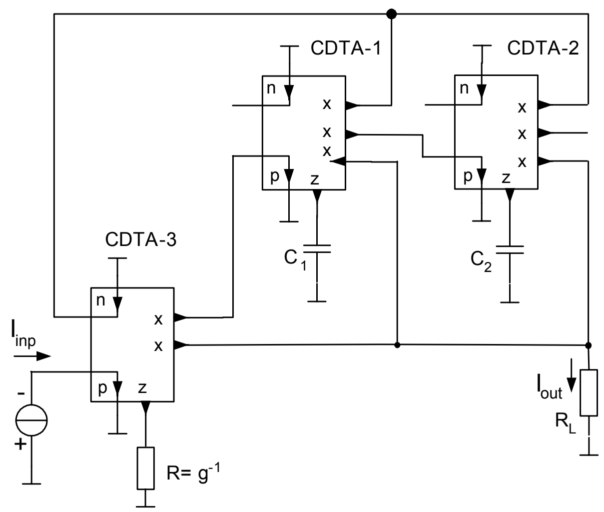


Fig. 8. Second-order all-pass filters with the CDTAs.

Furthermore, lower sensitivities and a smaller influence of parasitic capacitances can be obtained using the non-cascade connection given in Fig. 8. There the coefficients of polynomials (10) are simply given as

$$a_0 = \frac{g_1 g_2}{C_1 C_2}, \qquad a_1 = \frac{g_1}{C_1}, \qquad a_2 = 1 \; . \tag{11}$$

Equations (11) can be used for the filter design, which will be shown below.

7. Illustrative Example

To illustrate the given second canonical structure (FLF-OS) with CDTAs (Fig. 6), an all-pass filter was designed with the following specification: the constant group delay τ_g = 600 ns in the pass-band with the cut-off frequency f_c = 1 MHz, the filter operates in the CM and with the Bessel approximation.

In the first step, the order of the filter is determined n = 4 and the following coefficients of the desired transfer function (1) are obtained, using the filter design tool NAFID [10]

$$a_0 = 1.29715\ 10^{28},\ a_1 = 3.89065\ 10^{21}, \qquad a_2 = 5.00157\ 10^{14},\ \ a_3 = 3.33398\ 10^{7},\ \ a_4 = 1. \tag{12}$$

The circuit diagram of this all-pass filter given in Fig. 6 consists of four CDTAs with the transconductaces g_1, g_2, g_3, g_4 and four capacitors C_1, C_2, C_3, C_4 creating four current integrators (CI) and one current distributor (CD). This circuit has been symbolically analyzed by the SNAP computer tool [11] to obtain the current transfer function with the form of formula (1) and the following expressions for particular coefficients:

$$a_0 = \frac{g_1 g_2 g_3 g_4}{C_1 C_2 C_3 C_4}, \qquad a_1 = \frac{g_1 g_2 g_3}{C_1 C_2 C_3}, \tag{13}$$

$$a_2 = \frac{g_1 g_2}{C_1 C_2}, \qquad a_3 = \frac{g_1}{C_1}, \qquad a_4 = 1.$$

Substituting (12) into (13), the design equations are obtained. Then choosing the transconductances

$$g_1 = g_2 = g_3 = g_4 = g_5 = g = 1 \text{ mS}, \tag{14}$$

the resulting values of the capacitances are:

$$C_1 = 30 \text{ pF},\ C_2 = 67 \text{ pF},\ C_3 = 129 \text{ pF},\ C_4 = 300 \text{ pF}. \tag{15}$$

To verify the functionality of the proposed all-pass filter, the PSpice simulation has been carried out, using an adequate ABM model of the ideal CDTA. The resulting group delay frequency characteristic is shown in Fig. 9. It has confirmed the symbolical analysis and theoretical assumptions.

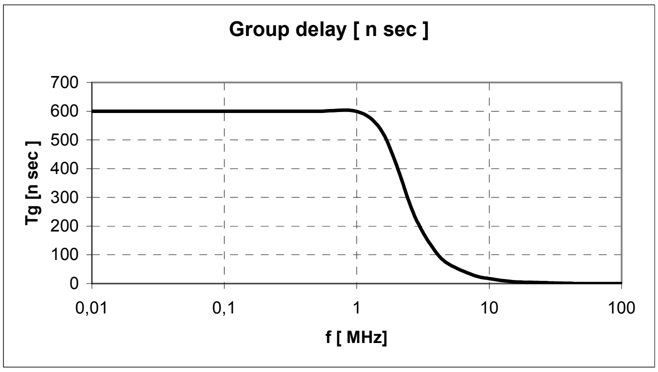


Fig. 9. Group delay response of the designed 4th-order filter.

8. Conclusion

This paper introduced first-, second- and higher-order analogue all-pass filters in the current mode, using multiple-output transconductors. More outputs give more possibilities in filter design. The design procedure was based o the signal flow graph technique. The graph of the n^{th}-order all-pass filter with canonical structure known in the standard voltage mode was modified and transformed into the current mode. The resulting signal flow graph was implemented by multiple-output integrators and current distributors using transconductors (OTAs and CDTAs). To illustrate and confirm the given structures an all-pass filter was designed and simulated by PSpice. The transconductors enable easy and direct implementation of other types of n-order filters operating in the current mode as low-pass, high-pass, band-pass and band-reject filters too. Note that using the same procedure, similar circuit structures can be obtained based on current conveyors instead of transconductors. All the filters mentioned here are fittingly electronically controllable by the transconductances (g_m) and auxiliary DC currents. These filters have the advantage of being in universal as regards type or function, and simple in direct design.

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Tomáš DOSTÁL was born in Brno, Czech Republic, in 1943. He received the degrees of CSc. (Ph.D) and DrSc. in electrical engineering from the Brno University of Technology in 1976 and 1989, respectively. From 1973 to 1978, and from 1980 to 1984, he was with the Military Academy in Brno, from 1978 to 1980 with the Military Technical College in Baghdad. Since 1984 he has been with the Brno University of Technology, where he is now Professor of Radio-Electronics. His present interests are in circuit theory, analogue filters, switched capacitor networks and circuits in the current mode.