Electronically Tunable Current-Mode Low-Pass Filter

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Abstract

This paper deals with the application possibility of the digitally programmable current follower in analogue signal processing. In connection with conventional double- and multiple-output current followers a current-mode low-pass filter is proposed. Using digitally programmable current followers the natural frequency of the proposed filter can be electronically adjusted. The advantage of the proposed structure is that to all nodes functional grounded capacitors are connected or they are at low impedance and virtually grounded. Hence, any parasitic capacitance will cause poles or zeroes at very high frequencies. The behaviour of the designed biquad has been verified by Spice simulations and, furthermore, by experimental measurements.

1. Introduction

The requirement of smaller chip area of integrated circuits processing analog signals leads to the usage of submicron technologies. Because of the specific dielectric strength of the material used it is necessary to decrease the supply voltage, which significantly affects the dynamic range and signal to noise ratio. It has been found that it is more suitable to design the circuits working in the current-mode where the information (or at least the information in the feedbacks) is transferred via currents [1], because even with low supply voltage sufficient value of the signal to noise ratio can be preserved.

The more frequent usage of current-controlled current sources signalizes the trend of transition to the current-mode. These elements are either simple current followers [2, 3] or they are current amplifiers [4] or followers with single input and differential output [5-8] or elements with differential input and single output [9] that might be suitable for high-frequency applications.

In this paper, using digitally programmable current follower (DP-CF) [6], together with conventional multiple-output current followers [10], a current-mode second-order low-pass frequency filter is presented. Using DP-CFs the natural or cut-off frequency, respectively, of the proposed biquad can be easily adjusted. Both Spice simulations and experimental measurements are presented that verify the feasibility of the filter designed, which is one of the main contributions of this paper.

2. Current Followers

A current follower (CF) is a device that transfers current signal from a low impedance virtually grounded input terminal to a high impedance output terminals.

Recently, the digitally programmable current follower has been presented that is realized through cascade connection of current division cells (CDC) [6]. It is a three-port active element with single input and differential output (Fig. 1a). The output currents can be expressed as

$$i_2 = \alpha \cdot i_1 \,,\; i_3 = -\alpha \cdot i_1 \,, \qquad (1a,b)$$

where

$$\alpha = \left(\frac{1}{2^{n+1}}\right)\left[1 + \sum_{i=0}^{n} \alpha_i 2^i\right], \qquad (2)$$

while n represents the length of the digital word, and α_i is the digital control bit of the CDC_i [6].

To create required current feedbacks in the filter topology double- (Fig. 1b) and multiple-output (Fig. 1c) current followers are used [10]. The relation between the input and output currents of the DO-CF are

$$i_2 = i_1 \,,\; i_3 = -i_1 \,, \qquad (3a,b)$$

while of the MO-CF

$$i_2 = i_3 = i_1 \,,\; i_4 = i_5 = -i_1 \,. \qquad (4a,b)$$

The usage of these active elements leads to the design of the current-mode filter, sometimes called as pure current-mode, i.e. not only the input and output signal is represented by current but, furthermore, all active elements used have only current input and output ports [11]. The advantage of such solution is that all nodes are at low impedance or grounded capacitors are connected to them. Hence, all parasitic poles and zeros are expected to be at very high frequencies.

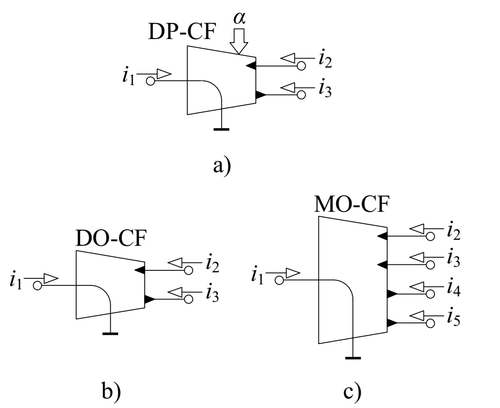

Fig. 1. Schematic symbol of a) DP-CF, b) DO-CF, c) MO-CF

3. Proposed Frequency Filter

The designed biquad using four passive and five active elements is shown in Fig. 2. The relation between the currents i_1, i_4, and i_5 from Fig. 2. can be expressed as

$$i_4 = -i_1 \,,\; i_5 = \alpha_1 i_1 \qquad \text{(5a,b)}$$

and hence for the three nodes, marked in the Fig. 2., it can be written

$$i_3 = I_{\text{IN}} + i_1 + i_2 \,, \qquad \text{(6a)}$$

$$i_2 + \alpha_1 i_1 + i_{\text{C2}} = 0 \,, \qquad \text{(6b)}$$

$$i_3 + \alpha_1\alpha_2 i_1 = i_1 + i_2 + i_{\text{C1}} \,. \qquad \text{(6c)}$$

Solving (6) the obtained current transfer function of the filter is

$$\frac{I_{\text{OUT}}}{I_{\text{IN}}} = -\frac{\alpha_1\alpha_2 G_1 G_2}{s^2 C_1 C_2 + s\alpha_1 C_1 G_1 + \alpha_1\alpha_2 G_1 G_2} \,, \qquad (7)$$

since $i_{\text{C1}} G_2 = i_2 s C_1$, $i_{\text{C2}} G_1 = i_1 s C_2$, and $I_{\text{OUT}} = \alpha_1\alpha_2 i_1$.

From (7) for $C_1 = C_2 = C$, and $\alpha_1 = \alpha_2 = \alpha$ the natural angular frequency ω_0 and quality factor Q can be expressed as

$$\omega_0 = \frac{\alpha\sqrt{G_1 G_2}}{C} \,, \qquad (8)$$

and

$$Q = \sqrt{\frac{G_2}{G_1}} \,. \qquad (9)$$

Comparing (8) and (9) it can be seen that the natural angular frequency can be adjusted by α independently of the quality factor.

Comparing the proposed structure in Fig. 2 with the ones in [2], [6], [7] it is not universal and provides only a low-pass response. It enables to control the natural frequency independently of the quality factor, which is the most required feature of low-pass filter [7]. However, adding another DP-CF between the negative output of the DP-CF$_1$ and the node 2 of the filter, the quality factor would be also independently adjustable.

Using the MO-CF$_1$, appropriate feedbacks are created that replace the voltage followers and reduce the number of floating passive elements in [2] and [7].

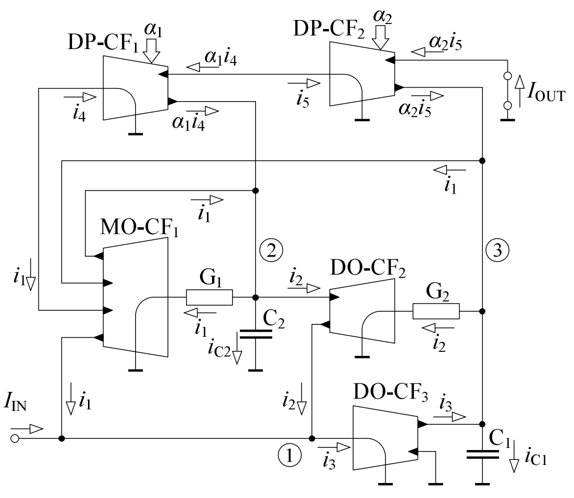

Fig. 2. Proposed frequency filter

4. Simulations and Experimental Measurements

The behavior of the proposed filter has been first verified by Spice simulations. The double- and multiple-output current followers have been simulated using the 3rd level model of the second-generation current conveyor and universal current conveyor respectively [12], those voltage ports Y are grounded (Fig. 3a,b). Both active elements are implemented in the UCC-N1B element that, based on the proposal of our workplace [13], has been produced in cooperation with AMI Semiconductor.

Similarly, by interconnection of the current amplifier EL2082 [14] and the second-generation current conveyor, the DP-CF is realized (Fig. 3c). The current gain of the EL2082 is controlled via analog voltage input, however it can be used to substitute the behavior of the DP-CF very well. The advantage of the EL2082 is that the values of the V_{SET} are the same as of α, i.e. if for example $\alpha = 1$, then $V_{\text{SET}} = 1$ V. However, the value of V_{SET} is limited and it is recommended to be in range zero to 2 V [14], but according to practical usage up to 5 V.

The values of the passive elements are $R_1 = 1/G_1 = 374\ \Omega$, $R_2 = 1/G_2 = 750\ \Omega$, and $C = 470$ pF for maximally flat magnitude ($Q = 0.707$). From (8a) for chosen values of the natural frequency f_0 ($f_0 = \omega_0/2\pi$) 300 kHz, 1 MHz, and 3 MHz the required values of the current gain α were determined to be 0.47, 1.57, and 4.70.

Since all active elements are available, experimental measurements were performed and compared with the simulations (Fig. 4). The filter responses were measured with the network analyzer 4395A, which has only voltage RF output and voltage inputs, hence appropriate V/I and I/V converters have been used (Fig. 5).

From the experimental measurements it can be seen that the real behavior of the proposed current-mode frequency filter

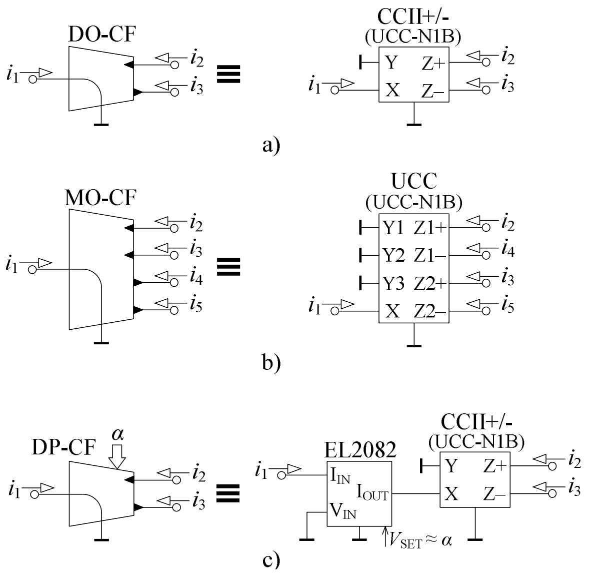

Fig. 3. Realization of a) DO-CF, b) MO-CF, c) DP-CF using UCC-N1B and EL2082

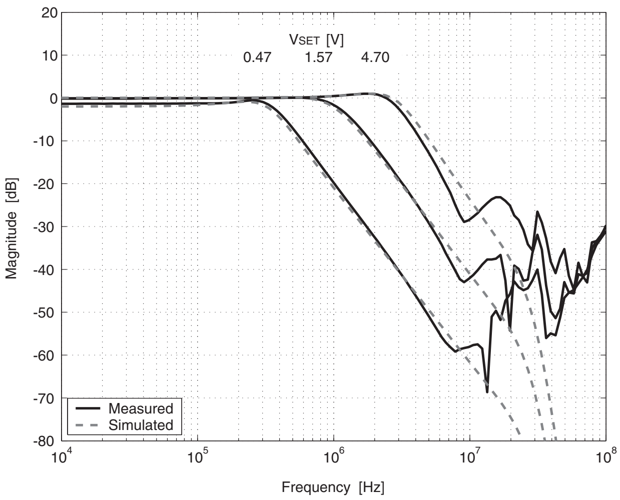

Fig. 4. Simulation and experimental measurement results

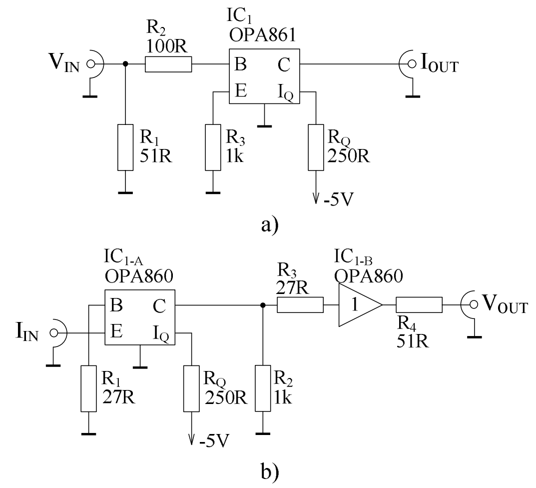

Fig. 5. a) V/I, b) I/V converter using OPA861 [15] and OPA860 [16]

largely agrees with the simulation results and is very satisfactory. At frequencies above 10 MHz the magnitude does not reach the values presumed by simulations. This is caused by the parasitic capacitance coupling between passive elements and also by parasitic capacitances between the outputs of the active elements used. However, the attenuation in this frequency area is always 20 dB or more.

5. Conclusions

In this paper current-mode low-pass filter has been presented, that employs current active elements only. Using the digitally programmable current follower the natural frequency of the filter can be electronically adjusted. The advantage of this solution is that to all nodes of the structure functional grounded capacitors are connected or they are at low impedance and virtually grounded. Hence, any parasitic capacitance will cause poles or zeroes at very high frequencies. The behavior of the proposed filter has been verified by Spice simulations. By proper replacement of the active elements used with the current amplifier EL2082 and universal current conveyor UCC-N1B experimental measurements were performed that furthermore support the feasibility of the structure and also are one of the contributions of this paper.

6. Acknowledgement

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