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SCALOR BASED TUNABLE HIGH-PASS SALLEN-KEY FILTER

BY

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Abstract. This paper presents the tuning performances of a second order high-pass Sallen-Key filter, using an x-controlled scalor that simulates a grounded electrically controlled resistance. The simulations have been made using a transistor level implementation of a current controlled current scalor, where the control parameter is I_x. Therefore, for a variation of I_x within the interval [56 μA; 100 μA], the filter central frequency varies from 61 kHz to 435 kHz.

Key words: x-controlled scalor; Sallen-Key filter, tuning; CMOS circuits.

1. Introduction

In recent years filter tuning techniques have received a considerable attention from integrated circuits designers. Many techniques for both central frequency tuning and quality factor tuning (Liu & Karsilayan, 2001; Gao & Snelgrove, 1998) have been reported in the literature. The tunable element can be a capacitor (Schaumann & Tan, 1989), a transconductance amplifier (Krummenacher & Joehl, 1988), a MOS resistive circuit (Osa *et al.*, 2001), etc. This paper exploits the possibility of using an x-controlled scalor (Goraş, 1979) for ω_c-tuning and Q-tuning in Sallen-Key filters.

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In a paper published by Brînzoi & Goraş, (2011), a technique of obtaining electrically controlled impedances using a current-controlled current scalor has been reported. The used scheme allows only the control of grounded passive elements. Therefore, this idea can be used only for filters which contain grounded elements. In this case, since the structure of the *x*-controlled scalor allows to implement only single-ended variable passive elements, frequency tuning and quality factor tuning for the presented filter cannot be made independently.

Even though, a second-order high-pass Sallen-Key has been analysed; this techniques can be applied to other types of filters as well.

2. Sallen-Key Second-Order High-Pass Filter

The Sallen-Key filter (Deliyannis, 1999) is a popular active filter which can be used to create second order filter stages that can be cascaded together to form higher order filters. The op-amp provides buffering between filter stages, so that each stage can be designed independently from the others. This paper is focused on a single stage design employing an *x*-controlled scalor for ω_c-tuning and Q-tuning.

The schematic for a high pass unity gain Sallen-Key filter is given in Fig. 1.

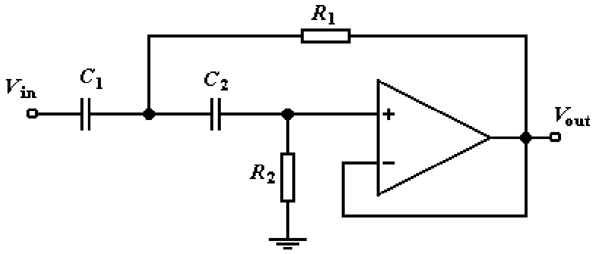

Fig. 1 – HP Sallen-Key filter.

The transfer function for this circuit is

$$H(s)=\frac{s^2}{s^2+s\left(\frac{1}{R_2C_1}+\frac{1}{R_2C_2}\right)+\frac{1}{R_1R_2C_1C_2}}, \tag{1}$$

the central frequency being

$$\omega_c=\sqrt{\frac{1}{R_1R_2C_1C_2}} \tag{2}$$

and the quality factor,

$$Q = \frac{\sqrt{R_1 R_2 C_1 C_2}}{R_1\left(C_1 + C_2\right)}. \tag{3}$$

For $C_1 = C_2 = C$

$$\omega_c = \frac{1}{C}\sqrt{\frac{1}{R_1 R_2}} \tag{4}$$

and

$$Q = \frac{1}{2}\sqrt{\frac{R_2}{R_1}}. \tag{5}$$

From (4) and (5) one can observe that for tuning ω_c and Q one can use R_1 or R_2 , but only R_2 is grounded. We choose R_2 to be realized as the input resistance of an x-controlled scalor loaded with a fixed resistor. The principle of the scaling technique is shown in Fig. 2.

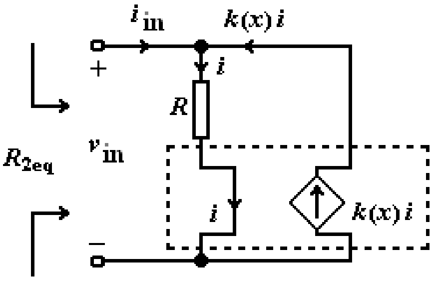

Fig. 2 – R_2 scaling method.

The input resistance of this circuit is

$$R_{2\mathrm{eq}} = \frac{R}{1 - k(x)}, \tag{6}$$

where R is the load and x will be a current (I_x).

3. Current-Controlled Current Scalor Nonidealities

For the transistor level implementation, reported by Brînzoi & Goraş (2011), a macromodel has been realized. It is represented in Fig. 3, and the components values are

$$C_{\mathrm{out}} = 0.54\ \mathrm{pF}, \tag{7}$$

$$R_{\text{out}} = 4.2007 - 0.0157 I_x \text{, (in μA), G}\Omega \tag{8}$$

$$r = 4.1\ \Omega. \tag{9}$$

One can observe that the component R_{out} depends on the control current, I_x.

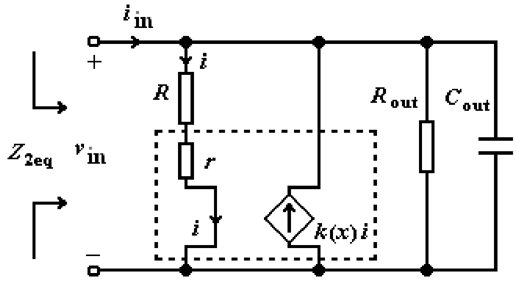

Fig. 3 – Current-controlled current scalor macromodel.

The expression of the input impedance is

$$Z_{2\text{eq}}(s) = \frac{1}{\dfrac{1-k(I_x)}{R+r} + \dfrac{1}{R_{\text{out}}} + sC_{\text{out}}}. \tag{10}$$

Replacing (10) in (1), one obtains the following filter transfer function:

$$H(s) = \frac{s^2}{a_2 s^2 + a_1 s + a_0}, \tag{11}$$

where the denominator coefficients are

$$a_2 = 1 + C_{\text{out}}\left(\frac{1}{C_1} + \frac{1}{C_2}\right), \tag{12}$$

$$a_1 = \frac{1}{\dfrac{R+r}{1-k(I_x)}}\left(\frac{1}{C_1} + \frac{1}{C_2}\right) + \frac{1}{R_{\text{out}}}\left(\frac{1}{C_1} + \frac{1}{C_2}\right) + \frac{C_{\text{out}}}{R_1 C_1 C_2}, \tag{13}$$

$$a_0 = \frac{1}{R_1 C_1 C_2 \dfrac{R+r}{1-k(I_x)}} + \frac{1}{R_1 R_{\text{out}} C_1 C_2}. \tag{14}$$

One can observe that the nonidealities of the implemented current-controlled current scalor do not change the filter order. Although, it alters both the central frequency and quality factor as follows:

$$\omega_c^{'} = \sqrt{\frac{\dfrac{1-k(I_x)}{R_1C_1C_2(R+r)} + \dfrac{1}{R_1R_{\text{out}}C_1C_2}}{1+C_{\text{out}}\left(\dfrac{1}{C_1}+\dfrac{1}{C_2}\right)}}, \tag{15}$$

$$Q^{'} = \frac{\sqrt{\dfrac{\dfrac{1-k(I_x)}{R_1C_1C_2(R+r)} + \dfrac{1}{R_1R_{\text{out}}C_1C_2}}{1+C_{\text{out}}\left(\dfrac{1}{C_1}+\dfrac{1}{C_2}\right)}}\left[1+C_{\text{out}}\left(\dfrac{1}{C_1}+\dfrac{1}{C_2}\right)\right]}{\dfrac{\left[1-k(I_x)\right]\left(\dfrac{1}{C_1}+\dfrac{1}{C_2}\right)}{R+r} + \dfrac{\dfrac{1}{C_1}+\dfrac{1}{C_2}}{R_{\text{out}}} + \dfrac{C_{\text{out}}}{R_1C_1C_2}}. \tag{16}$$

In order to determine the central frequency and the quality factor deviations from their values given in (2) and (3) one defines the relative error for both parameters as follows:

$$\omega_{c(\text{er})} = \frac{\omega_c^{'} - \omega_c}{\omega_c}\cdot 100,\ [\%], \tag{17}$$

$$Q_{(\text{er})} = \frac{Q^{'} - Q}{Q}\cdot 100,\ [\%]. \tag{18}$$

4. Design Example

The circuit in Fig. 2, with the macromodel in Fig. 3, was reported by Brînzoi & Goraş (2011), which design implementation have given. It has a 16 MHz bandwidth, so that a f_c less than 160 kHz has been chosen. In our case f_c = 100 kHz.

Since the number of unknown parameters is larger than the number of equations, some components will have to be selected freely. If we choose $C_1 = C_2 = 10$ pF, the resistors' values will be as follows:

$$R_1 = 112.54\ \text{k}\Omega, \tag{19}$$

$$R_2 = 225.08\ \text{k}\Omega. \tag{20}$$

The value of the resistance R, in Fig. 3, is of 15 kΩ. In order to obtain the value given in (20) for $Z_{2\text{eq}}$, a value of $I_x = 52.18\ \mu\text{A}$ for the control current is needed. Using these values in the relations (17) and (18), one obtains

$$w_{c(\text{er})} \approx 0.501\%, \tag{21}$$

$$Q_{(\text{er})} \approx 0.308\%. \tag{22}$$

5. Simulations

The small-signal response of the circuit proposed has been obtained by simulation. The performance of the transistor level implementation of the tunable resistor is compared to the cases when a macromodel or an ideal resistor is used. All the other components in the simulated circuit are ideal. The operational amplifier is implemented as a voltage controlled voltage source with a gain of 10,000. The magnitude and phase responses of the high-pass Sallen-Key filter for the three cases are illustrated in Figs. 4 and 5, respectively.

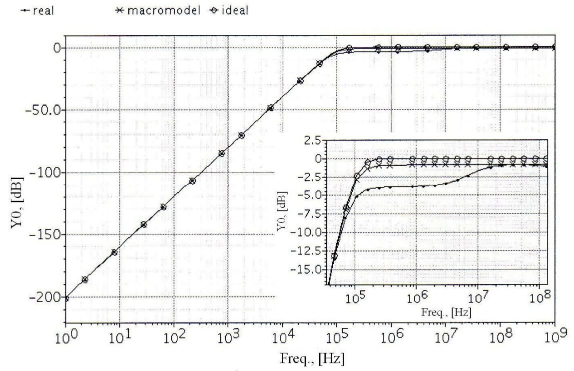

Fig. 4 – Filter response magnitude.

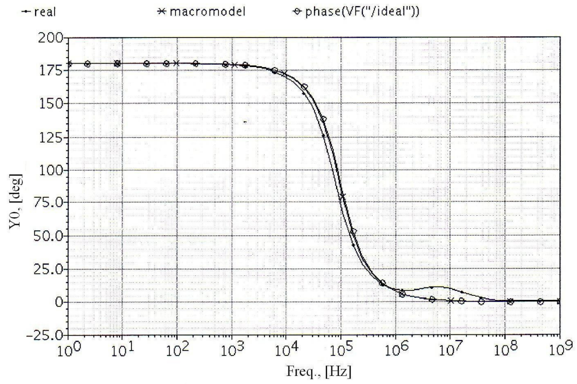

Fig. 5 – Filter response phase.

In Figs. 6 and 7 magnitude and phase responses of the designed filter for different values of the control current, I_x , are given. For these simulations the transistor level implementation of the current-controlled current scalor was used. We have found that when the control current, I_x, varies from 56 μA to 100 μA, central frequency varies from 61 kHz to 435 kHz.

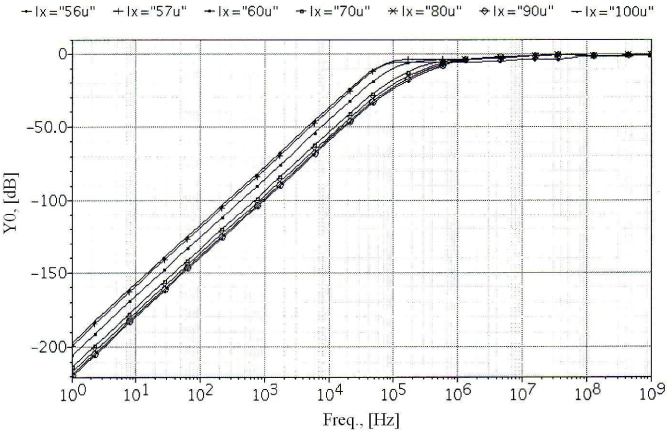

Fig. 6 – Real filter characteristics magnitude.

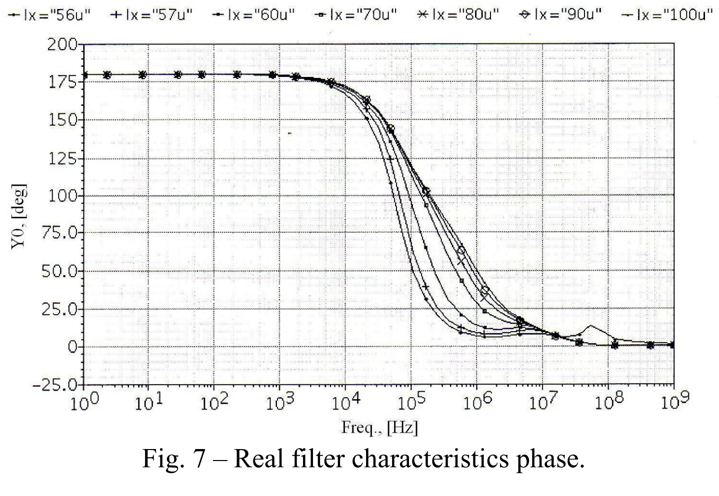

Fig. 7 – Real filter characteristics phase.

6. Conclusions

A second order tunable high-pass Sallen-Key filter has been presented. It uses a current-controlled current scalor transistor level implementation. The circuit design has been simulated in a UMC 0.18 μm technology and powered at 1.8 V.

The x-controlled scalor used for the implementation of the tunable resistance is limited to single-ended operation, which restricts the choice of tunable elements to single-ended ones. In this case it is not possible to achieve independent central frequency/quality factor tunning for the presented filter.

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FILTRU DE TIP SALLEN-KEY TRECE-SUS REGLABIL CU AJUTORUL SCALORULUI

(Rezumat)

Se prezintă un filtru Sallen-Key trece-sus reglabil. Frecvența centrală a acestui filtru este variată cu ajutorul unei rezistențe reglabile implementată folosind un scalor de curent comandat în curent. Proiectarea filtrului este însoțită de un exemplu numeric, iar pentru valorile obținute în urma acestuia s-au efectuat simulări în vederea confirmării metodei propuse de reglare a frecvenței centrale.

Simulările au fost făcute utilizând o implementare la nivel de tranzistor a scaloruului de curent comandat în curent, unde mărimea de comandă este curentul I_x. Astfel pentru o variație a curentului de control în intervalul [56 μA; 100 μA], frecvența variază de la 61 kHz la 435 kHz. De asemenea este reprezentat grafic răspunsul filtrului pentru trei cazuri în care rezistența reglabilă, R_2, este realizată utilizând o implementare CMOS a scalorului x-comandat, un macromodel al scalorului şi, respectiv, o rezistență ideală.