High-order BP Filter using Biquad Log-domain Method

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Abstract—High-order band-pass ladder filter based on log-domain biquad functions is presented in this paper. High-order ladder filter is designed from RLC ladder filter prototype on two types of biquad log-domain filters. Log-domain lossy and lossless integrator concepts are used to realize biquad log-domain filter in each type. Log-domain lossy integrator is easily realized by using 7 transistors and 1 grounded capacitor and log-domain lossless integrator is also easily realized by using log-domain lossy integrator by adding feedback to the input which consists of 8 transistors and 1 grounded capacitor. By adjusting bias current the frequency responses the filter can be obtain between 100 kHz and 100 MHz. This filter operates in transistor level which is suitable for operating in high frequency operation. A commercial array BJT technology is used in PSpice simulation.

Keywords—High-order filter, ladder, log-domain, tunable

I. INTRODUCTION

Continuous time filter is an essential function to selecting the desired signal and removing unwanted signals. Many applications are required the particular type of filters. In audio application, Low-pass (LP) filter is required to remove the noise and unwanted high-frequency carrier (class-D amplifier). Band-pass (BP) filter is required for selecting the particular frequency from the signal. In general case, low-order filter can be achieved the low-frequency solutions based on the basic circuits as Op-amp and RC networks. Moreover, if the frequency spectrum consists of many frequencies which are very near of each other. The general filter has no longer used in the special issue as well as in the telecommunications aspect.

The high-performance filter is an important building block especially in the telecommunication area. Recently, RLC passive filters are wildly used in telecommunications area, but they used of passive elements and lack of tunability feature which are not suitable in realizing integrate circuit. Active devices are considered to overcome the limitation of passive elements. First-order filters [1], [2] were presented with active devices but they still operate in low frequency responses. Second-order filters [3], [4] were presented. Integrators based on Op-amp [5-7] and OTAs [8-10] were proposed. Band-pass filter were presented by using CMOS [11], [12] in low frequency responses. Some works were designed by using high-order RLC ladder prototype [5-12] to realize high-order filters by various active building blocks, but they still have limitations in high frequency operation.

II. THEORY AND PRINCIPLE

A. Log-domain integrators

By using translinear log-domain cell [17] in Fig.1, we can obtain first-order low-pass filter function which can be called lossy integrator as

\[
\frac{I_{out}(s)}{I_{in}(s)} = \frac{-I_{out}(s)}{s + (1/CV_T)}
\]

Fig. 1. Log-domain lossy integrator and its block diagram

Lossless integrator can be achieved by looping back of lossy integrator as shown in the block diagram of Fig.2.

Fig. 2. Realization of lossless integrator from lossy integrator
The log-domain lossless integrator with inverting and non-inverting output is realized from lossy integrator by feeding back the non-inverting output to its input as shown in Fig.3, the transfer functions can be written as

$$I_n(s) = \frac{-I_{out1}(s)}{I_{out2}(s)} = -\frac{1}{sC_1V_r} \tag{2}$$

![Fig. 3. Log-domain lossless Integrator](image)

**B. Realization of Biquad Functions**

Biquad type-A is a special biquad function which performs a very high-Q BP filter. It can be realized by using two lossless integrators as shown in Fig. 4 and its transfer function can be written as

$$\frac{I_{out1}}{I_n} = \frac{-I_{out2}}{I_n} = -\frac{s(I/C_1V_r)}{s^2 + (I^2/C_1C_2V_r^2)} \tag{4}$$

![Fig. 4. Biquad filter Type-A](image)

In 2009 CMOS based universal biquad filters [19] with grounded capacitors are presented. The standard BP biquad filter can be realized by a lossy and a lossless integrator. This standard BP function is named as Biquad type-B and its transfer function can be expressed as

$$\frac{I_{out1}}{I_n} = \frac{-I_{out2}}{I_n} = \frac{s(I/C_1V_r)}{s^2 + s(I/C_1V_r) + (I^2/C_1C_2V_r^2)} \tag{5}$$

![Fig. 5. Biquad filter Type-B](image)

As the Biquad type-A block diagram, the log-domain version can be easily implemented by only lossless integrator from Fig.3 and with an additional negative output at a below integrator. Similarly, Biquad type-B in log-domain version can also be implemented by connecting the circuit in Fig.1 and Fig.3 with an additional negative output at a below lossy integrator.

**III. LADDER PROTOTYPE ANALYSIS**

Ladder network in Fig.6 is used to analysis resulting in the biquad functions. Node analysis theorem is analyzed based on the node voltages ($V_i$) and branch currents ($I_i$) whereas $i=2, 3, \ldots, n$. After that, all node voltages ($V_i$) have to transformed into the current form ($I_i'$). Also the impedances ($Z_i$) would be transformed in to the transfer function ($T_i$).

![Fig. 6. Generic ladder network with n branch currents](image)

By applying node analysis to Fig.6, we get eq.6-9. From eq. 6-9, block diagram of ladder network by using node analysis can be written as Fig.7.

$$I'_i = T_i(I_n - I_n) = \frac{Z_i}{Z_0}(I_n - I_n) \tag{6}$$

$$I_2 = T_2(I'_1 - I'_1) = \frac{Z_2}{Z_0}(I'_1 - I'_1) \tag{7}$$

$$I'_1 = T_1(I_2 - I_2) = \frac{Z_1}{Z_0}(I_2 - I_2) \tag{8}$$

$$I_4 = T_4I'_3 = \frac{Z_4}{Z_0}I'_3 \tag{9}$$

![Fig. 7. Node analysis block diagram of ladder network](image)

Sixth-order RLC Ladder band-pass filter prototype

Figure 8 shows Fifth-order RLC Ladder filter prototype that will be analyzed in this paper. By replacing RLC elements into impedances $Z_i$ to node analysis block diagram of ladder network in Fig. 7, the transfer functions in each phase can be written as

$$T_i = \frac{R_i}{Z_0} \tag{10}$$

$$T_1 = \frac{Z_1}{sL_1 + 1/(sC_1)} = \frac{sL_1/C_1}{s^2 + 1/LC_1} \tag{11}$$

$$T_2 = \frac{1/Z_2}{sC_2 + 1/(sL_2)} \tag{12}$$

$$T_3 = \frac{Z_2}{sL_1 + 1/(sC_1)} \tag{13}$$
Considering Eqs. (10)-(14), the transfer functions $T_2-T_4$ performed as biquad high-Q band-pass functions. They can be represented by biquad filter Type-A. For $T_1$ and $T_5$, they performed as current feedbacks of $T_2$ and $T_4$, respectively. The realization of sixth-order band-pass ladder filter is depicted in Fig.9. Considering Fig.9, there are current feedback itself at the beginning block and the last block (dotted line), so these two blocks can be replaced with $BQ$ type-B which consists of lower number of transistors. The minimized of a sixth order BP filter can be obtained in Fig.10.

Fig. 9. Sixth-order BP ladder filter synthesized from analysis

Fig. 10. Proposed minimized sixth-order BP filter

IV. SIMULATION RESULTS

To confirm the performance of proposed circuit, PSpice simulation results are carried out by using a bipolar array HFA3127 (NPN) and HFA3128 (PNP) technology as Table 1 for main log-domain circuits and their bias currents with 1.5V power supply. Fig.11 and Fig.12 show respectively biquad filter Type-A and Type-B frequency responses by varying the bias currents from 1µA to 1,000µA and given C=50pF.

Table 1 Bipolar model used for simulation

<table>
<thead>
<tr>
<th>Name</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$R_1$</td>
<td>100kΩ</td>
</tr>
<tr>
<td>$C_1$</td>
<td>1nF</td>
</tr>
<tr>
<td>$L_1$</td>
<td>10μH</td>
</tr>
<tr>
<td>$I_B$</td>
<td>1µA</td>
</tr>
<tr>
<td>$I_{ref}$</td>
<td>1mA</td>
</tr>
</tbody>
</table>

From the Fig.4, the log-domain biquad type-A function is a high-Q BP filter which can be verified by magnitude response in Fig.11. It is evident that the very narrow bandwidth BP filter can be obtained with tunable pole frequency along 100kHz to 100MHz based on bias currents between 1µA to 1000µA.

Fig. 11. Magnitude response of biquad type-A

Similarly, the log-domain biquad type-B function in Fig. 5 is a standard BP filter which can be verified by magnitude response in Fig.12. It is evident that standard BP response can be obtained with tunable pole frequency along 100kHz to 100MHz by the bias current between 1µA to 1000µA.

Fig. 12. Magnitude response of biquad type-B

The proposed sixth-order BP filter has been constructed by using the topology in Fig.10 based on the following elements: $C_1=C_2=C_3=160nF$ and $L_1=L_2=L_3=160nH$ are compared. The frequency response result in Fig. 13 shows the proposed filter and RLC prototype have a very small different in stop band at very low magnitude. At the passband, the proposed filter has a few more ripples compared with the ripple in RLC prototype.

Fig. 13. Magnitude response of proposed sixth-order BP filter compared to the RLC prototype
The proposed sixth-order BP filter also has a wide range tunability feature which inherited feature from log-domain method. The tunability feature has been verified by using the topology in Fig.10 based on all capacitors are 50pF and varied the bias current $I_B$ from 1µA to 1000µA. The center frequency of proposed BP filter was changed between 100kHz and 100MHz as the result in Fig. 14. It can be seen that at the bias current $I_B=1000\mu A$ give the quite high ripple at the high side of passband edge. Fig.15 illustrates the filtering performance based on $I_B=100\mu A$ which the in-band frequency (10MHz) can be selected. The very low amplitude of other frequencies were appeared cause by nearly passband frequency.

V. CONCLUSION

The log-domain high-order BP filter using the nodal analysis method is studied in this paper. From the analysis, the different biquad functions. The biquad functions can be realized by using the log-domain integrators. The nodal analysis is preferred for obtaining the branch currents and node voltage. All voltage parameters are transformed into the current parameters and also the impedances would also be transformed into the transfer functions. The log-domain biquad circuits are replaced the biquad functions and the number of transistors minimization is achieved by using different types of biquad circuits. The simulation results of the proposed filter are agreeable with the RLC prototype. The wide range tuned of frequency response can be achieved from 100kHz to 100MHz based on the varied of bias current from 1µA to 1000µA.

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