Realization of Transistor-Only High-Order Current-Mode Filters

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SUMMARY Linear transformation transistor-only high-order current-mode filters are presented in this Letter. Based on the systematic design procedure, we can realize high-order current-mode filters employing switched-current technique efficiently. Only two kinds of switched-current basic cells are needed in our design to obtain simple architectures. The fifth-order Chebychev lowpass filter is designed to verify the proposed synthesis method. Simulation results that confirm the theoretical analysis are obtained.

key words: transistor-only, high-order current-mode filters

1. Introduction

Filters have been found wide applications in instrumentation, automatic control and communication. A basic approach for building integrator-based high-order switched-current (SI) filters is to emulate a passive LC ladder filter which possesses low sensitivities in the passband [1]. Another design methodology for high-order SI filters employs the wave analog filter technology [2]. Voltage-mode high-order linear transformation (LT) filters are well developed in many literatures [3], [4]. But no paper discussed high-order current-mode linear transformation (CMLT) filters based on SI technique. LT filters have the advantages that every section of the original ladder prototype can be realized by using active elements individually. Furthermore, systematic design methods can be developed to simplify design procedures. In this Letter, a current-mode fifth-order Chebychev lowpass filter based on CMLT and SI technique is realized. Moreover, our proposed filters are suitable for integration.

2. CMLT and SI Basic Theory

The fundamental principle of the CMLT is based on the linear transformation which changes the port variables of a two-port network from the V-I domain to a new current x-y domain. For the two-port networks, nonsingular transformation matrices are introduced as follows:

\[
\begin{bmatrix}
    x_j \\
    y_j
\end{bmatrix} =
\begin{bmatrix}
    \alpha_{ji} & \beta_{ji} \\
    \gamma_{ji} & \delta_{ji}
\end{bmatrix}
\begin{bmatrix}
    V_j \\
    I_j
\end{bmatrix}
\]

\( j = 1, 2 \) and \( i = 1 \) to \( n \) (1)

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where \( n \) is the order of a filter, \( x_{ji} \) and \( y_{ji} \) have dimensions of amperes. The characteristics of original two-port networks can be modeled with transmission matrix, so \( y_{ji} \) can be found in terms of \( x_{ji} \). If \( x_{ji} \) represents the inputs and \( y_{ji} \) represents the outputs, we can describe a new two-port network. The ladder prototype is regarded as a cascade of the new two-ports.

Basically, only two kinds of SI basic cells [5] are needed in our design to obtain simple architectures. First, the differential-output current inverter (INV) with positive and negative current flows is shown in Fig. 1. Next, the differential-input differential-output bilinear integrator (INT) is proposed in Fig. 2. The latter is synthesized by the modified delay circuit. S1 and S2 are controlled by clock \( \phi_1 \), S3 and S4 are controlled by clock \( \phi_2 \), respectively.

Here, \( \phi_1 \) and \( \phi_2 \) are nonoverlapping clock signals.
Both of basic cells use cascode configuration to enhance their output impedances.

3. Design Procedure

Three different kinds of sections should be realized: input termination, output termination, and middle terminations. The choice of transformation matrices will affect sensitivities of a LT filter. Here, $\alpha_{ji}$ and $\delta_{ji}$ for shunt arms, and $\beta_{ji}$ and $\gamma_{ji}$ for series arms can be chosen to simplify the complexities of transformation matrices. Moreover, in order to reduce the numbers of SI basic cells, we can choose either $\alpha_{ji}$ or $\gamma_{ji}=\pm G$, and either $\beta_{ji}$ or $\delta_{ji}=\pm 1$.

In order to avoid the complexity of general interconnection between neighboring two-ports, we use cross-cascade interconnection as follows:

$$
\begin{bmatrix}
\alpha_{ji+1} & \beta_{ji+1} \\
\gamma_{ji+1} & \delta_{ji+1}
\end{bmatrix}
\begin{bmatrix}
1 & 0 \\
0 & -1
\end{bmatrix}
=\begin{bmatrix}
0 & 1 \\
1 & 0
\end{bmatrix}
\begin{bmatrix}
\alpha_{ji} & \beta_{ji} \\
\gamma_{ji} & \delta_{ji}
\end{bmatrix}
$$

So one can obtain

$$
\begin{bmatrix}
x_{ji+1} \\
y_{ji+1}
\end{bmatrix}
=\begin{bmatrix}
0 & 1 \\
1 & 0
\end{bmatrix}
\begin{bmatrix}
x_{ji} \\
y_{ji}
\end{bmatrix}
$$

For example, the input termination of a fifth-order lowpass ladder filter is connected to a current source as shown in Fig. 3(a). If we choose the transformation matrix as

$$
\begin{bmatrix}
\alpha_{21} & \beta_{21} \\
\gamma_{21} & \delta_{21}
\end{bmatrix}
=\begin{bmatrix}
0 & -1 \\
G & 0
\end{bmatrix}
$$

where $R_S = R_L = 1/G$

The output variables $x_{21}$ and $y_{21}$ can be expressed as

$$
y_{21} = \frac{D}{s + D}(J - x_{21})
$$

where $D = G/C_1 = G/C_5$

Then use bilinear transform

$$
s = \frac{2z^{-1}}{T (1 + z^{-1})}
$$

where $T$ is sampling period.

We can obtain

$$
y_{21} = \frac{A(1 + z^{-1})}{1 - Bz^{-1}}(J - x_{21})
$$

where

$$
A = \frac{TD}{2 + TD}, \quad B = \frac{2 - TD}{2 + TD}
$$

Output termination and shunt/series arms of a ladder filter can also be established in the same method. For the middle section of an LC-tank shunt section for series arms, for example, if we choose the transformation matrix as

$$
\begin{bmatrix}
\alpha_{1i} & \beta_{1i} \\
\gamma_{1i} & \delta_{1i}
\end{bmatrix}
=\begin{bmatrix}
G & 0 \\
0 & 1
\end{bmatrix}
$$

It can be seen that

$$
y_{1i} = y_{2i} = (\frac{s}{D} + \frac{K}{s})(x_{1i} - x_{2i}) \quad \text{where} \quad K = 1/\text{GL}
$$

We can get the following equation via bilinear transform

$$
y_{1i} = y_{2i} = \left(M \frac{1 - z^{-1}}{1 + z^{-1}} + N \frac{1 + z^{-1}}{1 - z^{-1}}\right)(x_{1i} - x_{2i})
$$

where $M = 2/\text{TD} \quad N = \text{TK}/2$.

It can be seen as the combination of the differentiator and the integrator.

For the output termination of a fifth-order lowpass ladder filter, if we choose the transformation matrix as

$$
\begin{bmatrix}
\alpha_{15} & \beta_{15} \\
\gamma_{15} & \delta_{15}
\end{bmatrix}
=\begin{bmatrix}
0 & 1 \\
G & 0
\end{bmatrix}
$$

We can also obtain

$$
y_{15} = \frac{A(1 + z^{-1})}{1 - Bz^{-1}}x_{15} = I_o
$$

According to the proposed design methods, CMLT SI-based filters can be synthesized by the following procedures:

(1) At first, the original ladder prototype is divided into several sections: input termination, output termination, middle terminations including series arms and shunt arms.

(2) Next, choose the appropriate transformation matrices as previous mention from the right output termination through middle series and shunt arms to the left input termination of the original ladder prototype to carry out their transfer functions.

(3) Use bilinear transform to obtain corresponding z-domain transfer functions.

(4) Then, replace the z-domain transfer functions with the corresponding SI-based circuits composed of basic cells, and connect neighboring sections with the cross-cascade interconnection.

(5) Finally, determine the values of W/L of MOSFETs via the $A$, $B$, $M$ and $N$ of derived design equations.
4. Design Example and Simulation Result

To demonstrate the efficiency of the proposed design method, a current-mode fifth-order Chebychev lowpass filters is realized. At first, for the Chebychev filter with 1 dB ripple and 2.5 MHz cutoff frequency in Fig. 3(a), we can divide the filter prototypes into five sections and choose appropriate transformation matrices to obtain their $z$-domain transfer functions. Here, we choose impedance scaling factor $K_m = 1k$, frequency scaling factor $K_f = 2\pi \times 2.5M$, sampling frequency $f_s = 10MHz$ to obtain the reasonable values. Then, replace them with the corresponding SI-based basic cells and join them together with the cross-cascade interconnection. Fig. 3(b) shows the completed circuit, and it employs only five current inverters and integrators. The circuit in Fig. 3(b) is simulated by using the HSPICE program with TSMC 0.35 $\mu m$ process. Here, $V_{DD} = -V_{SS} = 2.5V$ and the backgates of MOSFETs in Figs. 1 and 2 are connected to $V_{DD}$ for PMOS and $V_{SS}$ for NMOS, respectively. Its amplitude response of ripple is shown in Fig. 4. Simulation results that confirm the theoretical analysis are obtained. Fig. 5 is the physical layout of proposed filter. The core area of circuit approximates $433 \times 605 \mu m^2$.

5. Conclusion

High-order transistor-only linear transformation current-mode filters based on SI technique are presented. The filters can be realized by using proposed two kinds of basic cells. Our proposed filter has the following merits: efficient design procedures, simple design equations and systematic circuit architectures. Furthermore, the proposed filter is suitable for integration. The results will be useful for the current-mode filtering applications.

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References