Current-Mode High-Frequency Wavelet Filter for Communications

Wenshan Zhao[1, 2], Yichuang Sun[1], and Yigang He[2]

1. University of Hertfordshire, UK

2. Hunan University, China

Abstract: A novel method of designing high-frequency wavelet filter for communications is proposed. The Gm-C technique and current-mode leap-frog multiple loop feedback structure are employed. The Marr wavelet is utilized as an example to elaborate the design procedure. Using TSMC 0.18μm CMOS process, the center frequency of the Marr wavelet filter can be tuned from 60MHz to 129MHz. The total power consumption at 100 MHz is 112mW. Simulation results show the feasibility of the proposed approach.

1. Introduction

In the past few decades, there has been a great amount of interest in wavelet transform (WT) for signal processing, due to its time–frequency localization characteristics [1]. Particularly, WT has found an extensive range of applications in high–frequency signal processing of communication systems, e.g. modulation identification for communications [2], target detection in radar signal processing [3], and partial discharge detection and classification [4]. In order to achieve real–time performance, hardware implementations of WT have been investigated over the last few years, in which the digital circuitry is often employed [5,6]. However, due to the requirement of analogue-digital converter, the digital circuit implementations of WT suffer from the effect of large power consumption. In fact, as the industry is currently driving down the energy consumption, the high-quality low-power WT circuit is preferred for communication systems. To alleviate the difficulties associated with such digital designs, this paper proposes a method for analogue implementation of WT for high–frequency low-power application, in which a bank of Gm-C bandpass filters whose impulse responses are the wavelet bases (i.e. wavelet filter) is utilized.

Section 2 explains the characteristic of wavelet transform and the wavelet filter design procedure. Next, Section 3 describes the complete wavelet filter design using Gm-C technique, in which the fully-differential Nauta transconductor is employed as the Gm cell in order to enhance the performance. Then, the simulation results are presented in Section 4. Finally, Section 5 gives the conclusions.

2. Principle of Operation for Analogue Wavelet Filter Design

The wavelet transform consists of expanding functions over wavelets which are constructed from the mother wavelet (or wavelet base) $\psi(t)$ by means of dilations a and translations b [1],

$$WT_x(a,b) = a^{-1}\int x(t)\psi(\frac{b-t}{a})dt \tag{1}$$

where $x(t)$ is the input signal. The coefficient, $1/a$, maintains the amplitude of frequency response of $\psi_{a,b} = a^{-1}\psi(\frac{b-t}{a})$ across different scales.

So far, the popular methods for analogue implementation of WT mainly involves the rational function approximation of wavelet bases and the design of bandpass filters whose impulse responses are the approximated wavelet bases [7-9]. To facilitate the low-power operation, several important issues should be taken into consideration.

Firstly, an optimum rational approximation to the wavelet base resulting in a simple transfer function is desired, since simple transfer function will yield a compact circuit and thus low power consumption. Several mathematical techniques have been proposed to achieve the best possible approximation, among which the Taylor series approximation (TSA) can give a simple approximation rational function and reasonable approximation accuracy [8]. Thus, herein the optimal approximation provided in [8] is used to illustrate the wavelet filter design. Secondly, an optimum filter which can make a compromise between power dissipation and performances is desired. Generally, the filter's overall performances rely on both the filter structure and the building blocks (i.e. integrators). It is well known that current-mode circuits can offer many advantages, such as simplicity of circuit structure, high-frequency operation, wide dynamic range, and so on, compared with their voltage-mode counterparts [10]. Meanwhile, Gm-C based bandpass filter is regarded as the most popular technique for low-power high-frequency applications due to its simplicity and open loop operation [11].

Furthermore in view of filter synthesis, the multiple loop feedback (MLF) structure has been demonstrated to be well suitable for filter design since it has the characteristics of low magnitude sensitivity and uses only grounded capacitors, whilst cascade structure suffers from relatively high sensitivity and LC ladder simulation method requires floating capacitors.

On the basis of TSA method, a current-mode analogue wavelet filter using Gm-C leap-frog (LF) MLF structure is proposed in this paper.

3. Design of Current-Mode High-Frequency Gm-C Wavelet Filter

The MLF structure is general [10,11], which can realize any type of wavelet transform. But, for brevity, the Marr wavelet is taken as an example to elaborate the design procedure. As for the other wavelets, design in a similar way can be conducted.

3.1 Gm Circuit

Gm-C technique has been widely used for low power high frequency applications due to its simplicity and open loop operation. The performance of a Gm–C block relies strongly upon the characteristics of the transconductor employed. To optimize the elementary wavelet filter building blocks, the fully-differential Nauta transconductor is selected as the Gm cell in this filter [12], as shown in Fig.1. This transconductor has many advantages for high-frequency designs, such as no internal nodes to generate parasitic poles, relative high output conductance and possibility of large input and output voltage swing.

Fig.1 illustrates the basic fully-differential transconductor which is built up by invertors I_1 and I_2, while the invertors I_3-I_6 are introduced to guarantee common-mode stability and enlarge the differential-mode output resistance. The transconductance g_m is dependant on the supply voltage V_{dd}, which provides a means of tuning the filter.

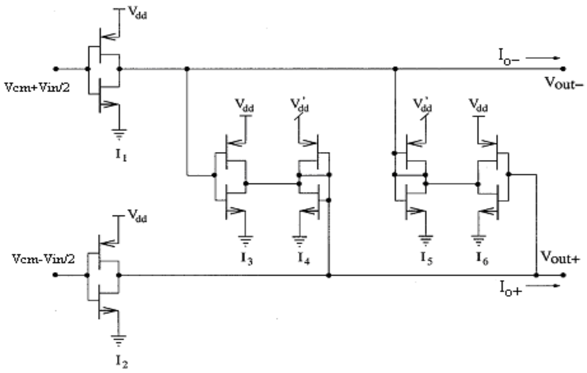

Fig.1. The complete Nauta transconductor

3.2 Filter Architecture and Synthesis

The normalized approximation function for Marr wavelet at a=0.1 proposed in [8] is given as:

$$H(s) = \frac{-6.88\times10^{-3}s^2}{D(s)} \tag{2}$$

Where $D(s) = 2.34\times10^{-8}s^7 + 1.34\times10^{-6}s^6 + 3.70\times10^{-5}s^5 + 6.79\times10^{-4}s^4 + 8.67\times10^{-3}s^3 + 0.075s^2 + 0.40s + 1$

The fully-differential realization of (2) using current-mode LF MLF structure with output transconductors producing zeros is shown in Fig.2.

Denoting $\tau_j = C_j / g_j$ and $\beta_j = g_{aj} / g_j$, the overall transfer function of the filter can be derived as

$$H(s) = \frac{I_{out}}{I_{in}} = \frac{N(s)}{D(s)} \tag{3}$$

Where $N(s) = \beta_5\tau_6\tau_7 s^2 + (\beta_5 + \beta_7)$

$$D(s)=\tau_7\tau_6\tau_5\tau_4\tau_3\tau_2\tau_1 s^7+\tau_7\tau_6\tau_5\tau_4\tau_3\tau_2 s^6+(\tau_7\tau_6\tau_5\tau_2\tau_1+\tau_7\tau_6\tau_5\tau_4\tau_3+\tau_7\tau_4\tau_3\tau_2\tau_1+\tau_7\tau_6\tau_3\tau_2\tau_1$$
$$+\tau_7\tau_6\tau_5\tau_4\tau_1+\tau_5\tau_4\tau_3\tau_2\tau_1)s^5+(\tau_7\tau_6\tau_5\tau_4+\tau_5\tau_4\tau_3\tau_2+\tau_7\tau_6\tau_3\tau_2+\tau_7\tau_6\tau_5\tau_2+\tau_7\tau_4\tau_3\tau_2)s^4+(\tau_7\tau_6\tau_3$$
$$+\tau_7\tau_6\tau_5+\tau_3\tau_2\tau_1+\tau_5\tau_2\tau_1+\tau_5\tau_4\tau_3+\tau_7\tau_4\tau_3+\tau_7\tau_6\tau_1+\tau_7\tau_2\tau_1+\tau_5\tau_4\tau_1+\tau_7\tau_4\tau_1)s^3+(\tau_7\tau_2+\tau_5\tau_4$$
$$+\tau_5\tau_2+\tau_7\tau_4+\tau_3\tau_2+\tau_7\tau_6)s^2+(\tau_7+\tau_5+\tau_3+\tau_1)s+1$$

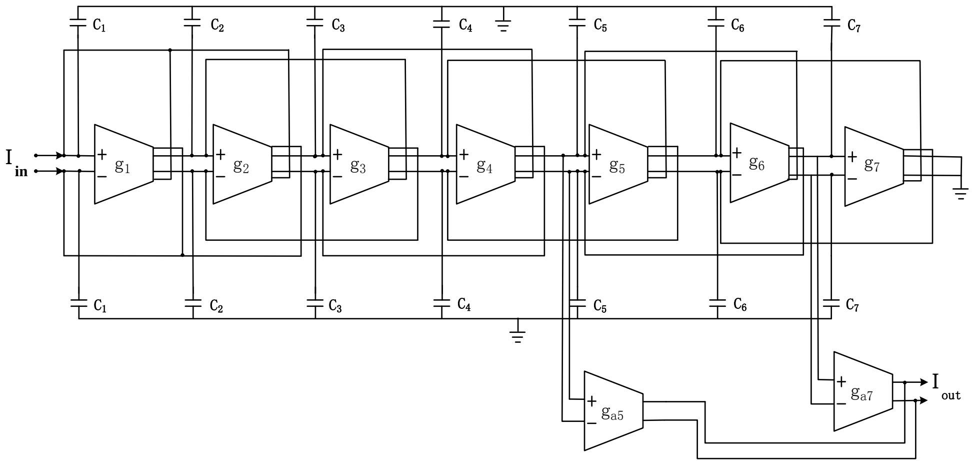

Fig.2. Fully-differential LF bandpass filter with output transconductors

Using the coefficient matching between the circuit transfer function in (3) and the desired characteristic in (2), the parameters in (3) can be determined as:

$$\begin{aligned}&\tau_1=0.017,\tau_2=0.053,\tau_3=0.088,\tau_4=0.112,\\&\tau_5=0.118,\tau_6=0.123,\tau_7=0.177,\beta_5=-0.317,\beta_7=0.317\end{aligned} \tag{4}$$

One can denormalize (2) to any desired centre frequency according to application requirement. Herein, the centre frequency is selected to be around 100 MHz as an example.

To improve transconductors matching and facilitate design automation, the integrator transconductors in Fig.2 are designed with identical transconductance 2mS. Thus, the transconductance g_{a5} and g_{a7} of the output transconductors can be calculated as -0.633mS and 0.633mS respectively, in which the negative transconductance can be realized simply by exchanging the two output terminals of the transconductor.

According to (4), the capacitors values in the filter can be obtained as below:

$$C_1=0.73pF,C_2=2.24pF,C_3=3.68pF,C_4=4.68pF,C_5=4.97\text{pF},C_6=5.17\text{pF},C_7=7.41p\text{F} \tag{5}$$

4. Simulation Results

The wavelet filter in section 3 is designed and simulated using standard TSMC 0.18μm CMOS process model with 1.8V power supply. Fig.3 shows the frequency response of the filter simulated by HSpice, achieving the center frequency 100MHz at V_{dd}=2.16V. The total power consumption of this filter is about 112mW at 100MHz. Simulation results have shown that the input equivalent noise is 210nV/√Hz at 100MHz, corresponding to a SFDR of about 38 dB. As seen from Fig.3, the performance of the proposed wavelet filter is confirmed by the excellent approximation of the 7^{th} – order rational approximation function.

By changing the transconductance values g_i, or capacitance values C_i, the wavelet filters at different scales can be implemented accordingly. The amplitude response of the complete filter with V_{dd} varied over the full tuning range of 1.6V-3.5V is shown in Fig.4. The tuning range of 60MHz-129MHz is achieved. The capacitance values C_i can be changed for different bands, with voltage change as fine tuning. Observed from these figures, simulation results indicate that the presented approach can easily implement the wavelet bases at different dilations and is very feasible for the application of WT at high and very high frequencies.

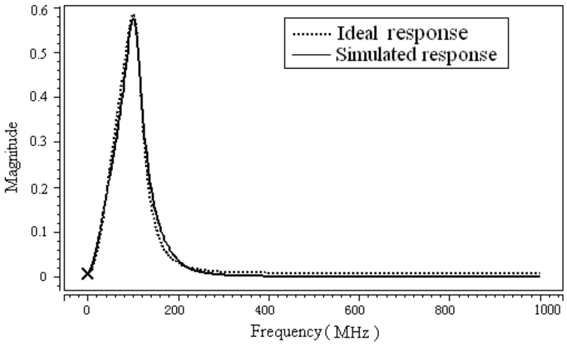

Fig.3. Frequency response of the wavelet filter at a=0.1

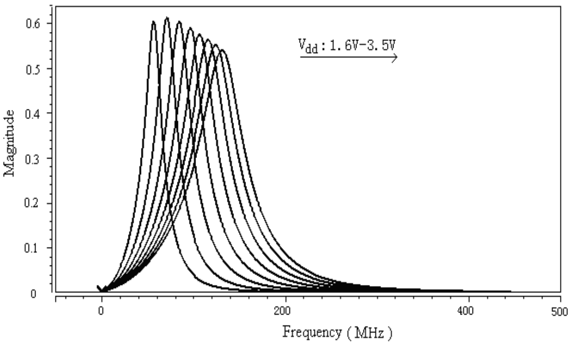

Fig.4. Frequency response of the wavelet filter over tuning range

5. Conclusions

To obtain a low-power high-frequency wavelet filter for communication systems, an analogue bandpass filter which employs a fully-differential Gm-C block based on the LF MLF structure is proposed in this paper. Taking the Marr wavelet as an example, the Nauta transconductor is used as the Gm cell in this wavelet filter in order to enhance the overall performance. Simulation results using 1.8V 0.18μm CMOS technology show an excellent approximation of the Marr wavelet base with 112mW power dissipation at 100MHz centre frequency. The wavelet filter is designed for 60MHz-129MHz tuning range. These results have shown that the wavelet filter can be used in real-time high-frequency signal analysis for communication systems.

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